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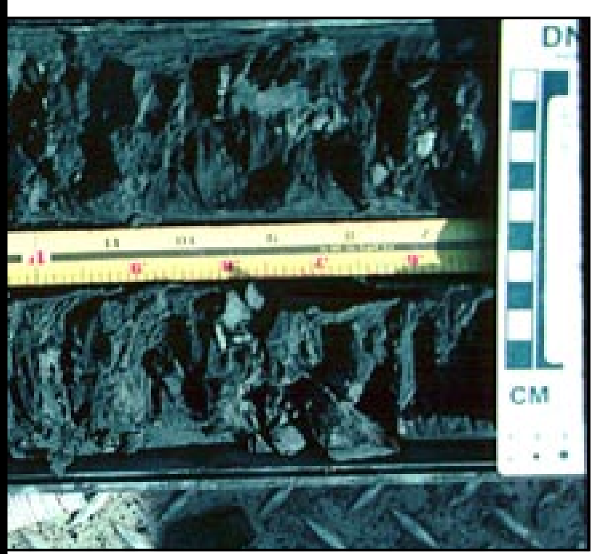
# Glacial Geology and Stratigraphy of Fort Richardson, Alaska

## A Review of Available Data on the Hydrogeology

Lewis E. Hunter, Daniel E. Lawson, Susan R. Bigl, Peggy B. Robinson, and Joel D. Schlagel

April 2000




**Abstract:** The surficial geology and glacial stratigraphy of Fort Richardson are extremely complex. Recent mapping by the USGS shows the general distribution of surficial deposits, but details on the underlying stratigraphy remain poorly known, leaving a critical gap in the understanding of ground water conditions below Fort Richardson. A conceptual model of the subsurface stratigraphy was developed on the basis of results of recent surficial mapping, current knowledge of the glacial history, studies of modern glaciers, and limited subsurface data. A confining layer below the southern half of the cantonment is likely the northern extension of an "older" ground moraine that crops out further to the south. Below the cantonment, this moraine is buried below about 15 m of outwash and fan deposits, but it appears to be absent to the north, where the confined and unconfined aquifers are hydraulically connected. The northern limit of the "continuous" ground moraine is roughly below the cantonment and parts of Operable Unit D. Buried silt horizons in the fan probably create the locally perched aquifers; however, erosional remnants of the ground moraine and interfingering of debris flow deposits along the Elmendorf Moraine are plausible alternatives. These deposits are composed of finer-grained materials that slow ground water infiltration and cause water to accumulate.

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April 2000

Prepared for
U.S. ARMY ALASKA

## PREFACE

This report was prepared by Dr. Lewis E. Hunter, Dr. Daniel E. Lawson, Susan R. Bigl, Research Physical Scientists; Peggy B. Robinson, Biologist, Geochemical Sciences Division; and Joel D. Schlagel, Physical Scientist (GIS), RS / GIS Center of Expertise, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| asl | above sea level |
| bgs | below ground surface |
| BP | Before Present |
| CRREL | U.S. Army Cold Regions Research and Engineering Laboratory |
| DRO | Diesel Range Organics |
| E&E | Ecology and Environment, Inc. |
| ENSR | ENSR Consulting and Engineering |
| ERF | Eagle River Flats |
| ESE | Environmental Science and Engineering, Inc. |
| GIS | Geographic Information System |
| GPR | Ground-Penetrating Radar |
| OHM | OHM Remediation Services Corp. |
| OU | Operable Unit |
| POLLDW | Petroleum, Oil and Lubricant Laboratory Dry Well |
| RRFTA | Ruff Road Fire Training Area |
| RRTSL | Roosevelt Road Transmitter Site Leachfield |
| S&W | Shannon and Wilson, Inc. |
| USACE | U.S. Army Corps of Engineers |
| USAF | U.S. Air Force |
| USARAK | U.S. Army Alaska |
| USGS | U.S. Geological Survey |

# Glacial Geology and Stratigraphy of Fort Richardson, Alaska
## A Review of Available Data on the Hydrogeology

LEWIS E. HUNTER, DANIEL E. LAWSON, SUSAN R. BIGL, PEGGY B. ROBINSON, AND JOEL D. SCHLAGEL

### INTRODUCTION

The distribution of surficial deposits across Fort Richardson is well known, based on more than 40 years of investigations (e.g., Miller and Dobrovolny 1959; Cederstrom et al. 1964; Karlstrom 1964; Schmoll and Dobrovolny 1972a; Reger and Updike 1983, 1989; Yehle and Schmoll 1987a,b, 1989; Yehle et al. 1990, 1992; Reger et al. 1995; Schmoll et al. 1996). Most of the Fort Richardson cantonment is situated on a large glacioalluvial fan, which originates at the mouth of the Eagle River Valley near the city of Eagle River (Fig. 1, Plate 1). The fan slopes gently to the west–southwest, underlying parts of Elmendorf Air Force Base and downtown Anchorage, and is truncated to the west by sea bluffs along the Knik Arm. The fan is composed of outwash deposited by ice-marginal streams and outburst floods that occurred when ice-dammed lakes in the Eagle River Valley drained (Schmoll et al. 1996). The glacioalluvial fan is bordered on the north by the Elmendorf Moraine, a low relief ridge that trends east to west across the region. The moraine formed about 13,000 $^{14}C$ years ago (Schmoll et al. 1972, 1996; Reger et al. 1995). Hummocky end- and ground-moraine deposits mixed with outwash, estuarine, lacustrine, and bog deposits are found north and northwest of the Elmendorf Moraine.

Along the southern margin of the fan and further to the south, several low hills of ground moraine protrude through younger glacial deposits of various origins from the most recent glaciation of this area (Plate 1). The streamlined hills located between the post housing area and Glenn Highway are such features (e.g., Birch Hill). These hills are composed of ground moraine (glacial diamicton) that extends underneath the fan deposits and probably below the Bootlegger Cove Formation, a fine-grained silt deposited in an estuarine environment (e.g., Miller and Dobrovolny 1959, Reger et al. 1995, Schmoll et al. 1996). The Bootlegger deposits and the ground moraine form an irregular surface upon which younger glacioalluvial sediments were deposited. Both the fine-grained diamicton of the ground moraine and the Bootlegger Cove Formation have much lower hydraulic conductivities than the overlying gravel and may confine ground water into multiple aquifers. Older gravel horizons that lie beneath these deposits form confined aquifers that appear to be hydraulically linked throughout the Anchorage area (Cederstrom et al. 1964).

This report summarizes the results of the initial phase of our hydrogeological study of Fort Richardson. Our goal was to synthesize existing surficial geology and stratigraphy information relevant to Fort Richardson, including a review of the glacial history of the Anchorage area. These data were then to be integrated into a conceptual stratigraphic model to provide a basis for future environmental studies and to help explain ground water behavior below the cantonment. The reason for this work is that the stratigraphic models typically used for environmental investigations on Fort Richardson are generally oversimplified, potentially leading to a false impression of subsurface conditions. This in turn could cause unwarranted conclusions to be drawn about the stratigraphy and its influence on ground water movement, affecting proper management decisions, and leading to ineffectual environmental cleanup efforts and compliance. This report documents the complexity of the stratigraphy on the

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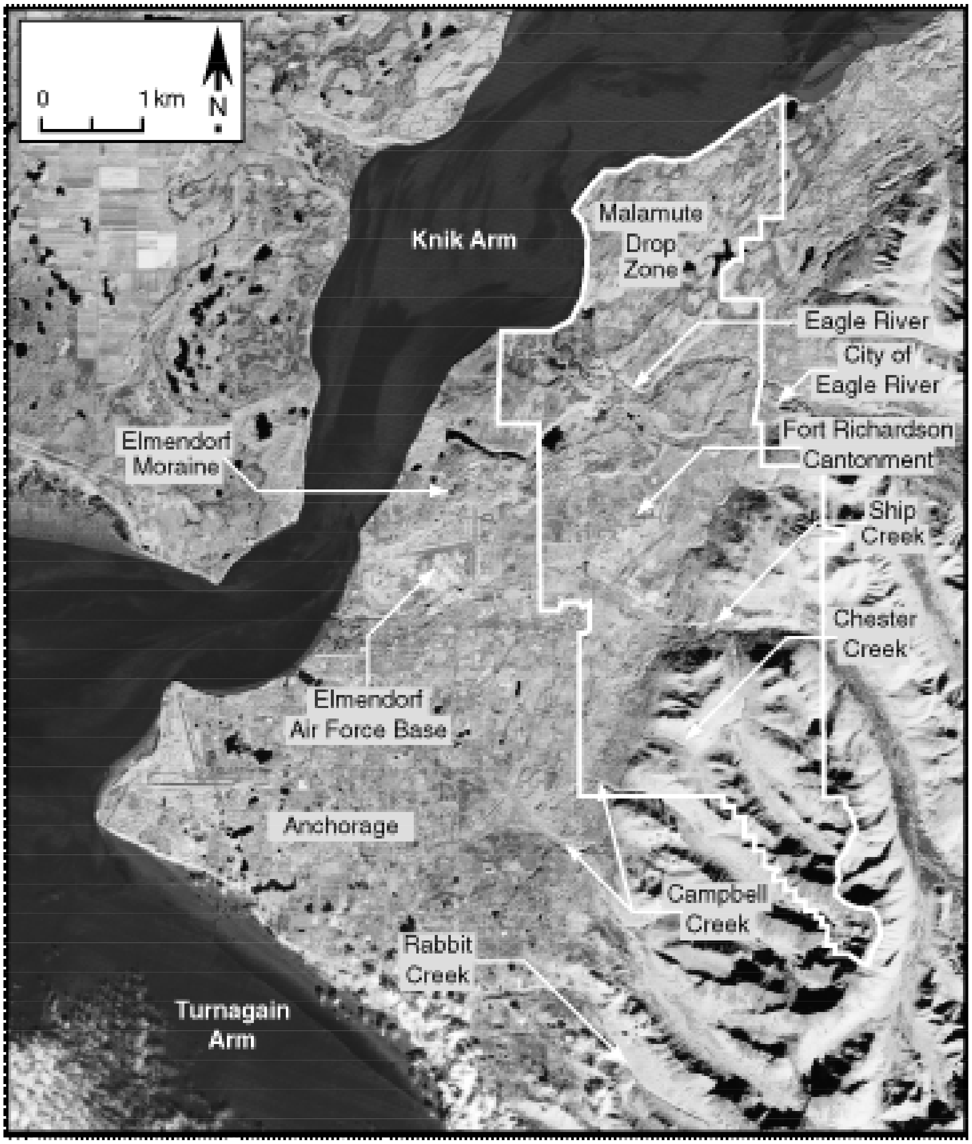


*Figure 1. General location of Fort Richardson, showing drainages described in the text (white line is border of fort).*

basis of data available at the start of the study. Field data collected following this study will be presented in a subsequent report.

**Physiography**

Fort Richardson lies in the Cook Inlet–Susitna Lowland and Kenai–Chugach Mountains physiographic provinces of Wahrhaftig (1965) (Fig. 2). The Anchorage Lowland is a roughly triangular area below 152 m elevation located between the Knik and Turnagain Arms. It is characterized by rolling hills with 15 to 76 m of relief. To the west, the terrain flattens across a broad alluvial plain that is locally incised by broad, shallow channels. The Anchorage Lowland is characteristic of glaciated terrain and contains various landforms, including hummocky moraine, drumlin fields, and outwash plains. Hills, mostly composed of glacial drift, lie at the base of the Chugach Mountains. These hills are separated by gently sloping alluvial fans formed by streams originating in the mountains. Rolling uplands border the Chugach Mountains and extend to elevations of 914 m.

The rugged Chugach Mountains rise abruptly to more than 2000 m along their front, with a flanking region of peaks and ridges generally 1000 to 1500 m high. Only the western flank of the mountains is contained in Fort Richardson, where elevations reach about 1615 m. The Chugach Mountains are cut by a series of northwest-trending U-shaped valleys, including those currently occupied by Ship Creek and Eagle River



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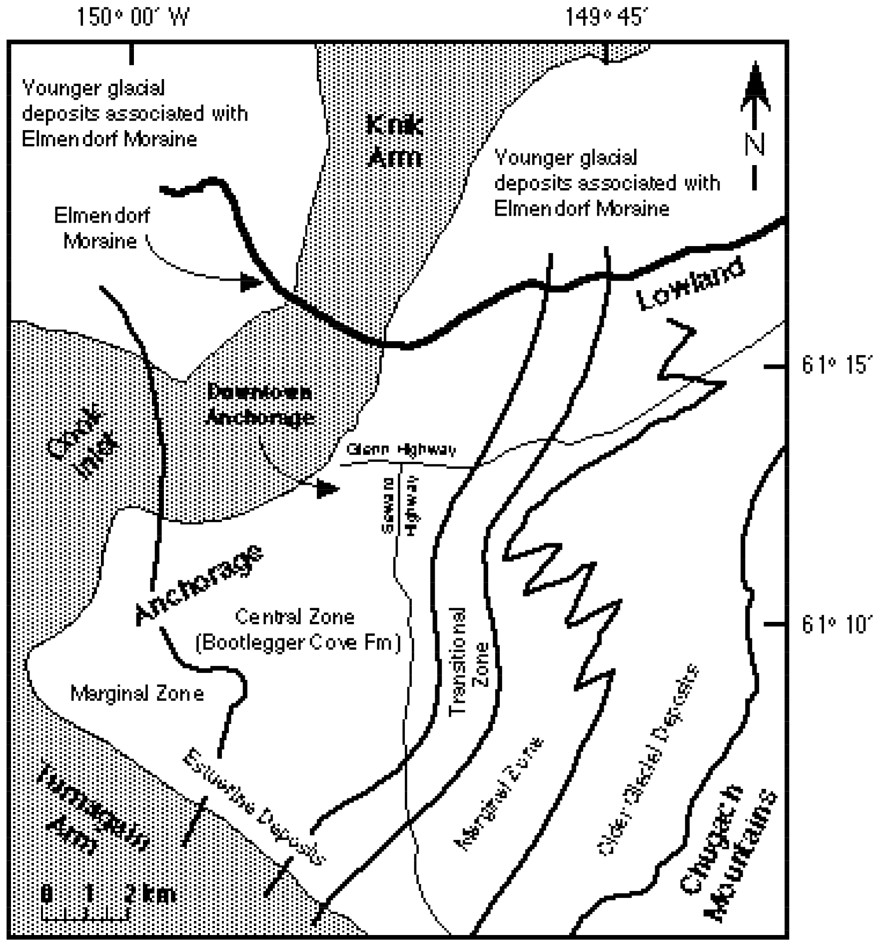


*Figure 2. Physiography of the Anchorage area and Fort Richardson. (After Yehle et al. 1986.)*

(Fig. 1). Generally sharp-crested ridges separate the U-shaped valleys, except to the northwest, where they become relatively smooth crested or gently sloping to nearly flat at their crests.

**Hydrography**

Fort Richardson lies primarily in the Eagle River and Ship Creek drainages; only the far southeast corner extends into the North Fork Campbell Creek drainage (Fig. 1).

The Eagle River drainage area covers 600 $km^2$ and is 12% glacier-covered (Munter and Allely 1992). The Eagle River flows in a well developed meandering channel, through a large U-shaped valley for about 32 km from its source in the Chugach Mountains. The last 10 km of this reach flows across glaciated lowlands on the north side of the Elmendorf Moraine (Fig. 1). The modern floodplain is incised into a paleo-outwash channel. The river straightens just east of Eagle River Flats. Here, channel migration has eroded uplands composed of stratified glacial sediments. The Eagle River discharges into the Knik Arm at the mouth of the Eagle River Flats, a macrotidal salt marsh (Lawson et al. 1996a,b). Mean annual discharge of the Eagle River at a gauging station in the City of Eagle River is about 15 $m^3/s$; discharge peaked in September 1995 at 292 $m^3/s$ during the greater than 500-year flood (Kemper et al. 1995, Brabets 1996).

Ship Creek emerges from the Chugach Mountains at the eastern edge of Fort Richardson and flows just south of the cantonment area (Fig. 1). Its channel is incised along the flank of the Chugach Mountains but becomes less so in the center of Fort Richardson where it crosses an old alluvial fan. Updike et al. (1984) described Ship Creek as being the most economically important stream in Alaska because it is used by three powerplants, and the Anchorage and Fort Richardson water treatment plants, as well as being the primary source of recharge to the Ship Creek aquifer (up to 14 million gal. [53,000 L] per day [Anderson 1977]). The mean annual discharge of Ship Creek is 16.5 $m^3/s$, with a peak discharge of 181 $m^3/s$, which occurred on 27 August 1989 (Brabets 1996).

Clunie Creek drains a small lake east of the

Malamute Drop Zone, flowing through a series of wetlands in an abandoned outwash channel, and discharges into the salt marshes of the Eagle River Flats. The old channel is incised into fluted ground moraine and represents a meltwater pathway that was active as Elmendorf ice retreated from the area (Plate 1).

Numerous tributaries including the south and north forks of Campbell Creek drain the western flanks of the Chugach Mountains south of Ship Creek. These eventually flow into Chester Creek west of the Fort Richardson border. The larger South Fork Campbell Creek originates in the Chugach Mountains, while the North Fork is fed by a series of unnamed and poorly defined streamlets that discharge from gullies along the mountains.

## SURFICIAL GEOLOGY

The geology of Fort Richardson and adjacent lands has been mapped by Miller and Dobrovolny (1959), Cederstrom et al. (1964), Schmoll and Dobrovolny (1972a) and more recently by Yehle and Schmoll (1987a,b, 1989), Yehle et al. (1990, 1992), and Schmoll et al. (1996). Other studies of the regional surficial geology have been made by Karlstrom (1964), Reger and Updike (1983, 1989), and Reger et al. (1995). The area is generally covered by deposits of glacial, glacial marine (glacioestuarine), and glacioalluvial origin, with bedrock outcrops found on the south and east along the Chugach Mountains (Fig. 1; Plate 1). These Quaternary-age sediments form a westward thickening wedge, beginning at the base of the Chugach Mountains, and locally reach about 213 m.* Below the Fort Richardson cantonment, these sediments are at least 70 to 98 m thick, based on well logs described by Cederstrom et al. (1964).

Because glacial sediments were deposited during multiple ice advances, they possess a complex

* Personal communication with H.R. Schmoll, USGS, 1996.

*Figure 3. Stratigraphic cross section from Fire Island (after Schmoll and Barnwell 1984) demonstrating the complex relationship among glacial sedimentary units.*



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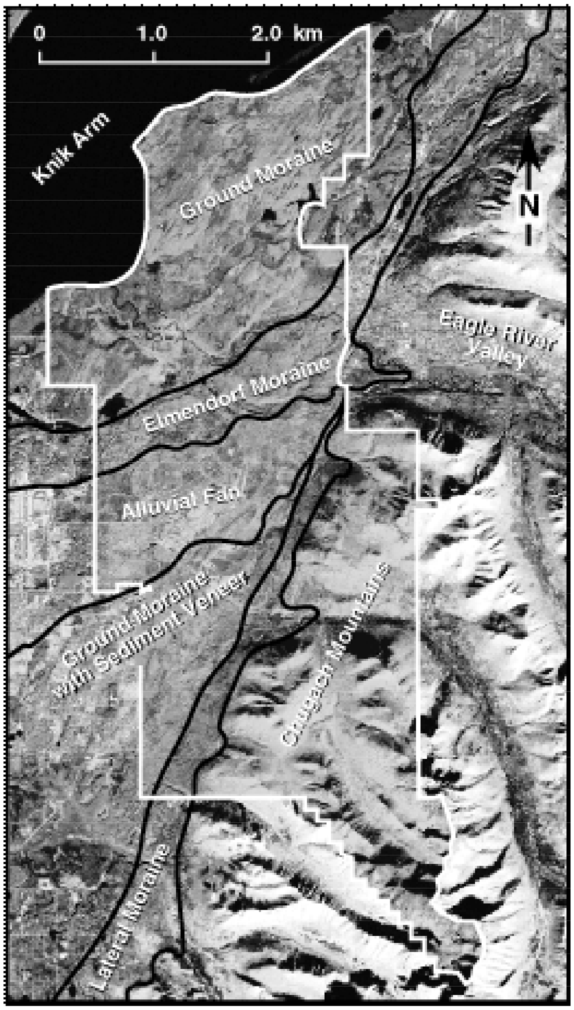

*Figure 4. Major landforms in the Anchorage Lowland.*

stratigraphy (e.g., Fig. 3). This complexity is especially true under the Fort Richardson cantonment area, where sedimentary deposits along the south margin of the Elmendorf Moraine likely interfinger with alluvial fan sands and gravels. These gravels are incised into or truncate ground-moraine deposits, while all of these deposits overlie older glacial and glacial marine deposits.

**Surficial geologic map**

We developed the conceptual stratigraphic model and interpreted the glacial history of the area largely on the basis of recent surficial geologic mapping by Yehle and Schmoll (1987a,b, 1989), Yehle et al. (1990, 1992), and Schmoll et al. (1996). These studies provide specific information on surface morphology and detail how the various sediments are distributed across Fort Richardson. A geological map of Fort Richardson (Plate 1) was produced by incorporating the geological data from five 1:24,000 topographic quadrangles. The original Mylar maps were provided to CRREL by H.R. Schmoll and L.A. Yehle, U.S. Geological Survey. A contracted company scanned these maps and converted raster data to vector data. Polygons were developed and labeled at CRREL to create an ArcInfo coverage of the surficial geology for the USARAK's GIS database of Fort Richardson. The map coverage has been reviewed by Schmoll and Yehle for accuracy and their detailed explanations of the map symbols are included as Appendix A. Our synthesis of the surficial geology is presented in the following sections.

**Surficial deposits**

The most common and spatially extensive surficial deposits on Fort Richardson are: 1) end moraine, 2) lateral moraine, 3) ground moraine, 4) glacioalluvial, alluvial, and alluvial fan, 5) estuarine, and 6) lacustrine (lake) (Fig. 4 and 5; Tables 1 and 2). Less abundant deposits are those of wind, colluvium, and rock glaciers. Wind deposits in the form of loess (wind blown silt) occur as a thin blanket of variable thickness throughout the area, but they have not been assigned a separate map unit. Colluvium, a poorly sorted, uncompacted, and unstable deposit of silt, sand, and gravel, is found along mountain slopes (solifluction and landslide deposits) and as a veneer on coastal and stream bluffs. Rock glaciers occur only in high mountain valleys. They consist of rock fragments with an ice matrix that allows them to flow.

*End-moraine deposits*

These are ice-marginal sediments deposited along the termini of glaciers. End moraines develop where the glacier remains relatively stable for an extended time. Deposition is polygenetic, resulting from combined fluvial (proglacial stream), glacial (lodgement, meltout, glacial-tectonic), and gravitational slope processes that produce gently arcing ridge complexes at the ice margin (Fig. 5). End moraines are composed of juxtaposed sequences of coarse gravel, fine well-sorted sand, dense silt and clay, and diamictons (App. A).

The Elmendorf Moraine is an end moraine that forms a major morphological feature across Fort Richardson just north of the cantonment area. It continues along the north edge of Elmendorf Air Force Base and in the Susitna Lowland across the Knik Arm (Fig. 1 and 4). Recent studies have shown that the Elmendorf Moraine correlates with ice advances in Turnagain Arm and

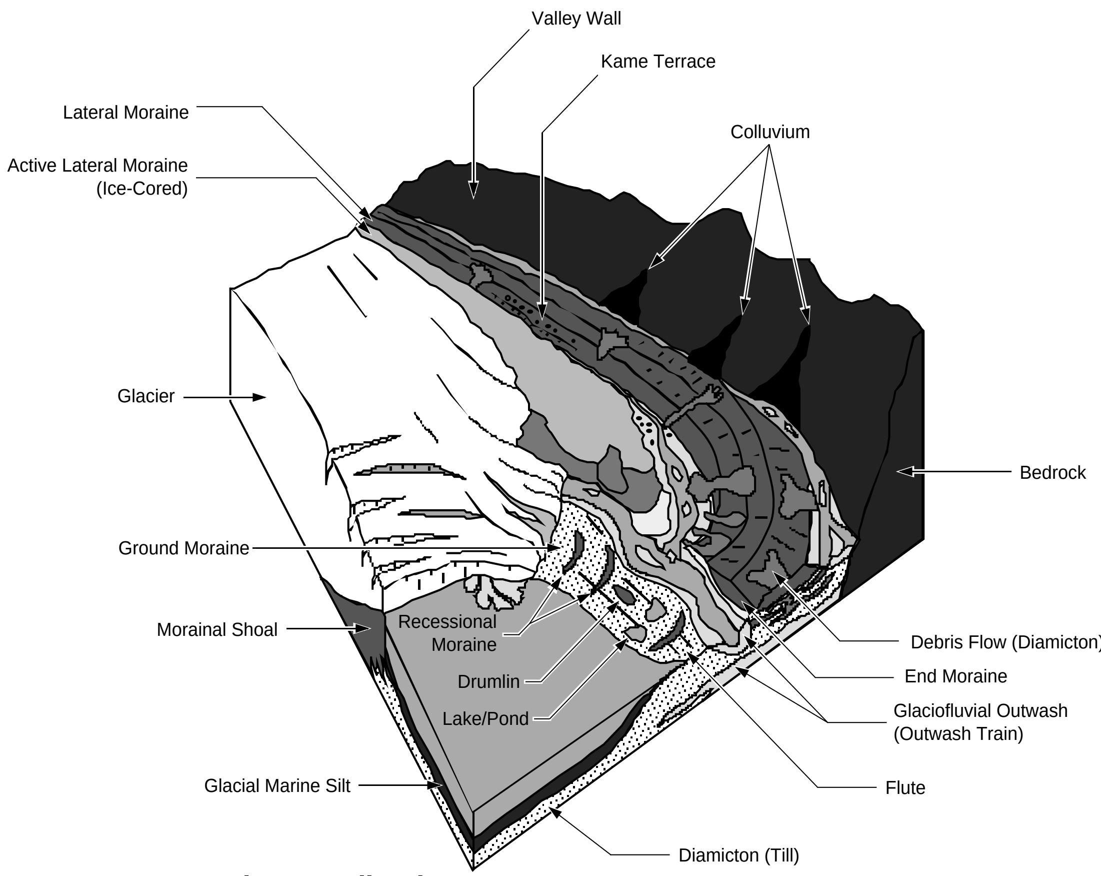


*Figure 5. How map unit types relate to a valley glacier. (After Boulton and Eyles 1979.)*

across south-central Alaska. It indicates a major regional advance between 14,000 and 13,000 $^{14}C$ years BP (before present) (Reger et al. 1995). There are also several smaller end moraines in the larger valleys of the Chugach Mountains (Schmoll et al. 1996).

*Lateral-moraine deposits*

These deposits develop as narrow, well-defined ridges and less well-defined ridge segments along the sides of glaciers. Lateral moraines are composed of sand, gravel, and diamicton, similar to end moraines (Fig. 5; Plate 1). Lateral moraines are found in the Chugach valleys and along the Chugach Mountain front. The latter ridges are aligned in an en-echelon pattern, descending gradually to the southwest. Older moraine ridges are generally better developed in the southwest, where they form the principal ridges along the base of the Chugach Mountains (Schmoll et al. 1996). Lateral moraines usually have gentle to moderate slopes along ridge tops, but steep sides, especially in the downslope direction. Where a ridge is relatively high on a mountainside, it may directly overlie bedrock. In other areas, they appear laterally gradational with colluvium on the mountain slopes while overlying other glacial deposits.

*Ground-moraine deposits*

Ground moraines form through a number of processes believed to operate beneath glaciers, most of which are not fully understood (e.g., Drewry 1986, Menzies and Shilts 1996). They are spatially extensive and commonly thinner than deposits of end and lateral moraines (e.g., Fig. 4 and 5; Plate 1). Ground moraines may be associated with positive-relief landforms, such as flutes and drumlins. They are generally composed of diamicton that may exhibit various degrees of sorting and stratification and may contain thin, interbedded sand, silt, and gravel horizons. These deposits are common north of the Elmendorf Moraine, where there are many drumlins and the surface is locally incised by modern and ancient alluvial channels and are of similar age to the

**Table 1. Characteristics of surficial deposits.**

| *Deposit* | *Materials* | *Topography and origin* |
|---|---|---|
| **Alluvial** | Well bedded and well sorted gravels and sands of variable thickness (few to tens of meters). Clasts are rounded to well rounded. | Smooth, with slopes nearly flat to very gentle; steep scarps locally separate deposits at different levels; deposits from active streams and floodplains. |
| Alluvial fan | | Conically shaped with slopes moderate to gentle, steeper near the fan apex. |
| **Colluvial** | Mainly loose, coarse rubble and rubbly diamicton, locally bouldery. | Smooth, with slopes generally steep to very steep and generally unstable; deposits that accumulate on a slope primarily poorly bedded and sorted through the action of gravity and secondarily with the aid of water. |
| **Glacioalluvial** | | Features or deposits associated with glacial streams. |
| Kame | Chiefly pebble and cobble gravel and sand, moderately to well bedded, in places chaotically. | Sharply hilly to hummocky with some local depressions; slopes moderate to steep; glacioalluvial deposit formed by running water within a glacier during early stages of stagnation and modified during ice meltout. |
| Kame-terrace | Chiefly pebble and cobble gravel and sand, moderately to well bedded and sorted. | Long, narrow landforms that have smoothly sloping surfaces with prominent scarps on their downslope sides; glacioalluvial deposits formed by water running along the side margin of a glacier. |
| Kame-channel | Chiefly pebble and cobble gravel and sand, locally may include some finer materials. | Slightly hummocky in broad, channel-like landforms of low relief; glacioalluvial deposits formed in ice-contact channels. |
| Meltwater-channel | Chiefly gravel and sand, well bedded and sorted; surface may include finer-grained material with thin organic accumulations. | Smooth with gentle slopes; channel-like deposits formed in areas recently abandoned by glaciers. |
| Outwash-train | Chiefly pebble and cobble gravel and sand, well bedded and sorted. | Smooth with gentle slopes except steep at terrace edges; accumulated mainly in front of end moraines, downstream of meltwater-channel deposits. |
| **(Glacio) Estuarine** | Chiefly silty clay, silt, and fine sand, well bedded and sorted; locally includes thin beds of peat and other organic material; also locally includes diamicton, coarser sands, and gravels. | Smooth with slopes nearly flat; locally marked by subdued hills and irregularities; accumulated in ancestral Cook Inlet marine environment, coarser facies deposited at glacier tidewater margin. |
| **(Glacio) Lacustrine** | Interbedded clay, silt, and sand; well to somewhat poorly sorted. | Smooth with gentle slopes, but very steep at valleyward margins; accumulated in freshwater bodies (large lakes to small ponds) ponded by glacier ice or moraine deposits. |
| **Moraine** | | A mound, ridge, or other accumulation of glacial sediment producing a variety of landforms. |
| End moraine | Juxtaposed sequences of deposits from polygenic origins, primarily diamicton (poorly sorted admixtures of silt, sand, and gravel) along with coarse gravel, fine well-sorted sand, dense silt, and clay, moderately to well compacted. | A gently arcing ridge or series of ridge segments deposited at the end (or terminus) of a glacier. |
| Lateral moraine | Sand, gravel, and diamictons. | A ridge or ridge segments deposited at the side margin of a glacier. Commonly form gently sloping, sharp-crested ridges along the walls of valleys that glaciers formerly occupied. |
| Ground moraine | Diamicton of variable thickness; may contain thin, interbedded sand, silt, and gravel horizons, and thin outwash gravel or lake deposits on the surface. | Smooth to hummocky, with gentle to moderately gentle slopes; deposits left behind when glaciers retreat. |
| **Pond and bog** | Chiefly peat; includes organic-rich silt, minor woody horizons, and thin interbeds of ash-sized tephra. | Smooth with very gentle slopes; accumulated in ponds or small former lakes or stream channels that filled with organic material. |
| **Rock glacier** | Mainly angular to some subrounded rock fragments being actively transported; contains ice-rich matrix; fines from cobble- and boulder-size fragments at surface to more rubbly diamicton character at depth. | Moderately hummocky and rough, slopes moderate to very steep; mixture of rock fragments and ice-rich matrix is transitional between a true glacier and a slow-moving landslide. |

**Table 2. Processes of recharge and discharge in Anchorage Lowland.**

| *Recharge* | *Discharge* |
|---|---|
| **Unconfined aquifer** | |
| Stream infiltration (losing reaches) | Stream channels (gaining reaches) |
| Rain / snowmelt percolation | Seeps / springs |
| Discharge along mountain front | |
| **Confined aquifer** | |
| Percolation from unconfined aquifer | Percolation to unconfined aquifer under high hydrostatic head |
| Seeps from fractured bedrock | Lateral discharge into unconfined zone where confining layer is intersected |
| Discharge along mountain front artesian flow to surface or bluffs | |

Elmendorf Moraine. An older ground moraine of Late Wisconsin age lies at depth south of the cantonment area.* It appears sporadically at the surface, where it protrudes through younger glacioestuarine and alluvial fan deposits, and likely underlies the sediments across much of Fort Richardson.

*Glacioalluvial, alluvial, and alluvial fan deposits*

*Glacioalluvial*. These are a suite of deposit types, including kame-channel, meltwater-channel, and outwash-train deposits, consisting of water-laid sediments deposited in front of a glacier (Fig. 5; App. A). Meltwater-channel deposits are composed of well-bedded and well-sorted sand and gravel, which may include some finer-grained material that was deposited in a shallow backwater. Thin organic horizons are also common on the surface of fine-grained deposits. Thickness is highly variable, often 1 m to a few meters, but in places channel deposits may be thin and patchy, allowing ground moraine or bedrock to crop out at the channel floor. Stratified sand and pebble- to cobble-size gravel form outwash-train deposits, which accumulated in front of the Elmendorf Moraine and downstream from Chugach valley glaciers. Most of these latter deposits now occur mainly in terraces along former channels. Kame-channel deposits are composed of sand and pebble- to cobble-size gravel, similar to outwash-train deposits. Some silt and clay may now fill paleo-topographic depressions. Thickness is generally at least a few meters and the deposits have a hummocky surface that may be incised with low relief channels. Kame-channel deposits are common at the transition between high-relief kame and ground-moraine deposits.

Glacioalluvial sediments deposited along glacier margins have a distinctly hummocky morphology caused by the meltout of glacier ice, which was buried beneath them (Fig. 5). This melting commonly disturbs the overlying sediments and further complicates the stratigraphy. Several types of kame deposits can be recognized; most are generally composed of thin beds of sand, silt, diamicton, and gravel, with varying degrees of bedding and sorting. Irregular hills from meltout include those near the margin of the Elmendorf Moraine, within the Elmendorf Moraine north of Clunie Creek and at the margin of the Anchorage Lowland downslope of major mountain valleys (Plate 1). These deposits are moderately loose, but compact in the center of some hills and commonly may merge with end- and lateral-moraine deposits. They are often characterized by sharp crests and more rounded hummocks, moderate to steeply dipping slopes, and sometimes are truncated by stream channels.

Kame-terrace deposits were formed by water running along the glacier margin. Long, narrow landforms with smoothly sloping surfaces develop. Prominent scarps may remain where deposition was in contact with the glacier. Kame-fan deposits, which also form at the glacier margin, range from several to a few tens of meters in thickness. Their topography is generally smooth, and surfaces are relatively moderate, with gentle slopes increasing in steepness towards their ice source.

*Alluvial*. Both modern and ancient alluvial deposits are found on Fort Richardson. They occur along present day streams and floodplains (Fig. 1; Plate 1), often incised into older glacioalluvial and alluvial fan deposits. The deposits are commonly well-bedded and well-sorted sands and gravels of variable thickness (a few to tens of meters). Clasts are rounded to well rounded. Both modern and ancient stream deposits have nearly flat to gentle slopes. Scarps 1 m to several meters high may locally separate deposits from

* Personal communication with H.R. Schmoll, USGS, 1996.

*Figure 6. Interbedded alluvial sediments as might be produced by periodic discharge events (sand and gravel) and silt deposition in abandoned channels. (After Selly 1976.)*

different periods, forming a series of terraces that represent several periods of downcutting.

Alluvial deposits on the east side of the Anchorage Lowland are composed primarily of well-bedded and well-sorted sand and gravel derived from local mountain-valley sources. Contacts are generally well defined and the morphology reflects alternating periods of deposition and incision. Well-developed terraces are common at all levels, with the nested fans emanating from incised channels. These fans formed both before and after the incursion of the Eagle River, while some of the higher-level deposits are probably similar in age to outwash of the Elmendorf and older glacial advances.

*Alluvial fan*. Fan deposits are common across the area. Important deposits include 1) a large fan emanating from the Eagle River Valley, 2) smaller fans from local valley sources, and 3) fans along the edge of the Elmendorf Moraine. Alluvial fans are composed of well stratified and sorted sand and gravel.

The largest of these deposits on Fort Richardson is the Mountain View fan, which emerges from the Chugach Mountains at the south edge of the Eagle River Valley (Fig. 4; Plate 1). The Mountain View fan extends from the Chugach Mountains to Knik Arm in the area between the Port of Anchorage and Turnagain Heights and lies below most of the Fort Richardson cantonment (Miller and Dobrovolny 1959). This particular fan has multiple levels (nested or composite morphology), reflecting a complex history of formation by recurrent, sudden breakout discharges from an ancient glacial lake in the Eagle River Valley, in a manner similar to Lake George discharging into the Knik River (Post and Mayo 1971). The result is a complex assemblage of flood and interflood deposits (Fig. 6) that reach a thickness of 15 to 18 m and are composed of a cobble gravel near the head of the fan (see Hunter et al. 1997). Further west and downslope, the size of material decreases from gravelly sand to fine sand. A high percentage of fines (10–15%) is described in borehole logs from the cantonment area (USACE 1996b), the amount increasing with depth.* Locally (e.g., Ruff Road Fire Training Area, E & E 1996), sand and gravel may be interbedded with fine silt and clay.

Also there is a series of small, well-developed

* Personal communication with H.R. Schmoll, USGS, 1996.



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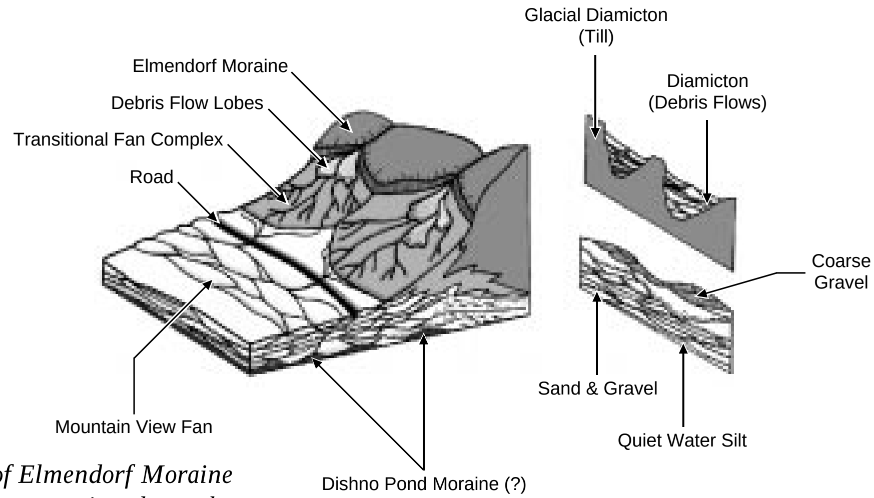



*Figure 7. Incised fans in flank of Elmendorf Moraine and interfingering of sedimentary units along the moraine margin.*

fans along the southern margin of the Elmendorf Moraine (Fig. 4; Plate 1), with their apices in small channels cut into the moraine (Fig. 7). The well-preserved fan morphology tells us that they were active during the late stages of moraine formation (Plate 1). Because the toes of these fans are not truncated, they were probably created during late phases of Mountain View fan formation and may have developed after the catastrophic discharges from the Eagle River Valley. Elmendorf ice must have remained close enough to its maximum position at the terminal moraine to provide sediment and water to the aggrading fans and to keep meltwater from being diverted into the ancestral drainages of Six Mile Lake or Eagle River to its north.

*Estuarine and glacioestuarine sediments*

Estuarine deposits are formed in present-day Cook Inlet and its major arms, Knik and Turnagain, or along similar water bodies of the recent past (Fig. 2 and 4). Glacioestuarine deposits accumulated in an ancestral Cook Inlet that probably differed from the present-day inlet in configuration because of base level changes and the presence of glaciers.

Modern estuarine deposits are peripheral to Cook Inlet, where macrotidal fluctuations of 7–9 m intermittently expose recent silty deposits. Older Holocene estuarine deposits occur extensively at the upper end of Knik Arm and in Eagle River Flats (ERF). Estuarine deposits are generally composed of well-bedded and sorted silt and fine sand, and may locally include thin beds of peat, driftwood, and other organic or windblown material. Deposits of this unit are commonly several meters to a few tens of meters thick and consolidated (e.g., Combellick 1990, 1991, 1994).

Glacioestuarine deposits of late Pleistocene age accumulated in an ancestral Cook Inlet that was larger and deeper than at present, although no true shorelines have yet been identified.* The upper limit of marine submergence during this time may have been as great as 183 to 213 m above modern levels (Yehle and Schmoll 1987a, 1988), although Karlstrom (1964) suggests water may have been as high as 305 m above present sea level. Deposits that consist of varying combinations of interbedded diamicton, stony silt, fine sand, silt and silty clay, and coarse sand–gravel often indicate deposition at elevations above present sea level, probably with ice terminating in water nearby.

A major stratigraphic unit considered glacioestuarine in origin is the Bootlegger Cove Formation (Bootlegger Cove Clay of Miller and Dobrovolny [1959], redesignated as Formation by Updike et al. [1982]). It was apparently deposited during a much higher sea level, when ice that created the Elmendorf moraine advanced into the area (Reger et al. 1995). The unit is composed of silty clay and clayey silt, sometimes interbedded with silt, fine to medium sand, and thin diamicton beds (Updike et al. 1988). Brackish-marine microfossils are present throughout much of the formation (Schmidt 1963, Smith 1964), which reaches a thickness of 35 m (Updike et al. 1988). This unit occurs widely throughout the subsurface at elevations typically below about 30 m asl, and underlies surficial deposits exposed in the Elmendorf Mor-

*Personal communication with H.R. Schmoll and L.A. Yehle, USGS, 1996.

aine in bluffs on Knik Arm (Miller and Dobrovolny 1959, Cederstrom et al. 1964). The Bootlegger Cove Formation is exposed principally in the southern part of the Anchorage Lowland near Campbell Creek and along numerous sea and stream bluffs, where it is commonly concealed beneath other deposits (Plate 1). It is likely that a sandy facies of the Bootlegger occurs along the former basin margin and locally interfingers with deposits of the Elmendorf Moraine. This is a transitional zone, where coarse clastic sediments were contemporaneously deposited adjacent to fans and streams.

*Lacustrine and glaciolacustrine deposits*

Lacustrine deposits accumulate in bodies of water ranging from large lakes to small ponds, and include water bodies closely associated with former glaciers as well as those formed after their retreat. Kame-fan deposits are transitional between glacioalluvial and glaciolacustrine deposits and are found where ice dams temporarily impounded water along the glacier margin. Thicker glaciolacustrine deposits accumulate in large lakes in valleys blocked by the glacier. Deltas commonly prograde into the lakes where outwash streams enter them. Other lacustrine deposits originate in lakes behind moraines or landslides. Deposits similar in nature also originate in ponds that fill topographic depressions, such as in hummocky ground moraine. Bogs form as ponds fill in with organic material and may accumulate thick layers of peat.

Glaciolacustrine deposits consist of interbedded clay, silt, and sand, and may include occasional layers of gravel or diamicton. The deposits range from well to poorly sorted and contacts are generally well defined. Surface topography is generally smooth, with gentle slopes that increase in steepness towards valley margins. The silt and clay are moderately stable, except in contact with colluvium on valley walls, where they are susceptible to stream erosion and failure.

Along the Elmendorf Moraine, lake deposits reach thicknesses of 5 to 10 m and may be much thicker beneath alluvial and peat deposits that form the floor of the upper part of Eagle River Valley. Correlative deposits are found in major mountain valleys from Eklutna River south to the Eagle River Valley. Older deposits occur along Ship Creek, the lower slopes of Peters Creek, and the South Fork Eagle River up to an elevation of 100 m asl and reach a thickness of about 10 m in the bluffs of Thunder Bird Creek.

Pond and bog deposits (peat and organic-rich silt, minor woody horizons, and interbeds of ash-sized tephra) are widespread in the Elmendorf Moraine, the floor of Eagle River Valley, and locally in lateral moraines. Bog deposits may overlie silt, clay, marl, or fine-grained sand that first accumulated in small lakes or along stream channels. These deposits commonly reach 4 m in thickness, but may locally exceed 10 m.

## GLACIAL GEOLOGICAL HISTORY

Glacial deposits in the Anchorage area have traditionally been divided into broad age groups that span much of the Quaternary Period (e.g., Miller and Dobrovolny 1959; Karlstrom 1964; Reger and Updike 1983, 1989; Reger et al. 1995). The earlier studies thought that at least five major glaciations affected the Cook Inlet region, extending back more than 200 ka BP (Ulery and Updike 1983). Their chronological control was derived from relative age dating techniques and minimal conventional radiocarbon data. More recently, Yehle and Schmoll (1987a,b, 1988, 1989), Yehle et al. (1990, 1991, 1992), and Schmoll et al. (1996) have attributed most of the surficial deposits to multiple advances and retreats of the last glaciation (Late Wisconsinan). Rapid changes from glacial to marine and terrestrial environments produced abrupt shifts in depositional processes. These rapid changes, taking place as the glacier margin fluctuated over both the short and long term, may account for some of the seven or more glaciations interpreted from the borehole data by Trainer and Waller (1965) and Schmoll and Barnwell (1984).

Below, we review the glacial history of Anchorage according to Schmoll et al. (1996) and Reger et al. (1995). An understanding of how the glaciers fluctuated and deposited their sediments is required for us to develop a conceptual stratigraphic model of the cantonment area. Such an overarching idea is required to evaluate the hydrogeology of Fort Richardson, so that ground water flow patterns and contaminant transport can be evaluated, because detailed geological data on the subsurface are generally not available. So, the conceptual model is therefore based on knowledge of the glacial history and sedimentary processes (Lawson 1979, 1981, 1982, 1988; Boulton 1968, 1970, 1971, 1972, 1975; Powell 1980, 1981, 1984a,b; Hunter et al. 1996a,b).

The sequence of events during the last glaciation is as follows.

- *Stage 1* corresponds to full glacial conditions reached prior to 20,000 years BP. Glaciers flowed out of the Chugach and Talkeetna Mountains, where they coalesced and flowed into the Cook Inlet–Susitna Lowland. Ice filled Knik Arm, overtopping some of the ridges along the Chugach Mountains, and flowed into the isostatically depressed Cook Inlet. Lateral moraine deposits from this time correspond to the Rabbit Creek Moraines.
- *Stage 2* is the retreat from full glacial conditions, probably beginning around 18,000 to 20,000 $^{14}$C years BP. A marine transgression (sea inundation) accompanied retreat to an unknown position in Cook Inlet.
- *Stage 3* is a stillstand or minor readvance of the glaciers, with multiple fluctuations in the ice margin that resulted in deposition of some of the Fort Richardson moraines. Marine conditions extended to Rabbit Creek and South Fork Campbell Creek about this time.
- *Stage 4* is a retreat of unknown distance, which allowed a marine incursion that extended north to at least the North Fork Campbell Creek and Chester Creek areas. The lowermost sediments composing the Bootlegger Cove Formation were deposited during this incursion.
- *Stage 5* is a readvance that deposited the Dishno Pond moraines in the eastern lowland area (Plate 1). Marine conditions remained in the Campbell Creek and Chester Creek areas, with additional marine sediments deposited to form additional Bootlegger sediments.
- *Stage 6* corresponds to the final retreat of the ice from the Dishno Pond moraines and progressive recession up-valley out of the lower Knik Arm. Ice-rafted debris in the base of the Bootlegger Cove Formation indicates tidewater conditions and glaciers calving icebergs into the sea (Schmidt 1963) around 14,900 ± 350 $^{14}$C years BP (Schmoll et al. 1972, Reger et al. 1995). Reger et al. (1995) concluded that the Bootlegger Cove Formation was deposited between about 15,000 and 13,000 $^{14}$C years BP. The extent of ice retreat up Knik Arm is not known; however, marine silt equivalent to the Bootlegger Cove Formation can be found about 60 km up the Susitna Valley (Reger et al. 1995). Marine submergence during the initial phase of ice retreat was about 140 m above mean sea level and was probably followed by isostatic uplift shortly after the ice retreated. Coastal processes active along the Hillside area and Fort Richardson moraine would have eroded these older morainal sediments up to the level of submergence.
- *Stage 7* is a major readvance of the ice margin around 13,500–14,000 $^{14}$C years BP into Knik Arm. This advance probably occurred behind a marine shoal that protected most of the glacier's terminus from tidewater conditions (e.g., Post 1975, Mayo 1988) (Fig. 8). The uppermost units of the Bootlegger Cove Formation were deposited then. These units contain sand layers and generally coarsen upwards (Miller and Dobrovolny 1959, Karlstrom 1964, Yehle et al. 1986), apparently recording the increased proximity of the ice or a shoaling, or both, during ice advance. Termination of this advance constructed the Elmendorf Moraine. Reger et al. (1995) estimate that at the end of the Elmendorf advance, land began to emerge from the sea at about 13,500 $^{14}$C years BP. Land emergence, ice shove, and glacial tectonic uplift of sediments was probably attributable to a combination of high sedimentation rates near the glacier margin and isostatic uplift after the ice receded.

Ice or moraine dams at the mouth of the Eagle River Valley periodically broke, causing rapid drainage of lakes impounded in the valley. Such catastrophic flooding would cause intense, local scour as water was deflected across the front of the Elmendorf Moraine. Recurrence of these events likely produced the Mountain View fan that originates at a narrow gap between the Elmendorf Moraine and Chugach Mountains near the city of Eagle River. The fan forms a sand and gravel plain that extends across the Anchorage Lowland to Knik arm (Fig. 4). As ice began to retreat from the Elmendorf Moraine, ancestral channels of the Eagle River were reoccupied as new channels became incised, providing lower elevation drainages and shorter routes to the Knik Arm.

- *Stage 8* represents a rapid retreat of ice from the Elmendorf moraine. The hummocky topography in the Susitna Valley and upper Knik Arm are indicative of ice stagnation and downwasting. Reger et al. (1995) suggest that ice margin retreat probably reached the

Palmer area around 9000 $^{14}C$ years BP, about the same time as when ice retreated to the Turnagain Pass area at the head of Turnagain Arm. It is not known whether or not marine submergence accompanied retreat up Knik Arm. Silt and clay deposits found on the surface north of the Elmendorf Moraine may point to a short phase of submergence beneath the sea or deposition in small lakes that could have developed in the hummocky glacial deposits. Numerous stream channels were incised into the Elmendorf Moraine, as well as at multiple locations farther north. These now-abandoned channels were active near the ice margin during its retreat. Most of the landforms (hummocks, drumlins, flutes, ground moraine, etc.) north of the Mountain View fan were deposited during the advance and retreat of the Elmendorf ice.

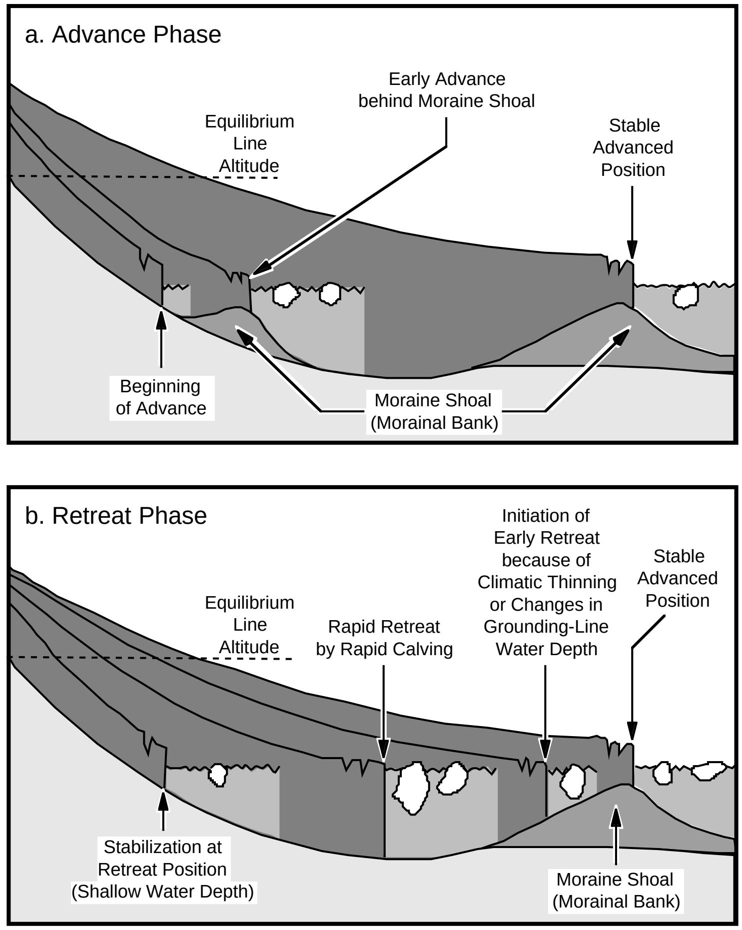



*Figure 8. How a tidewater glacier can advance (a) into the marine environment as long as a moraine shoal protects it from deep water. Retreat (b) begins when deep water conditions are reestablished and it continues until shallow water is reached. (After Mayo 1988.)*

## CONCEPTUAL STRATIGRAPHIC MODEL

Surficial deposits near the cantonment area are 70 to 98 m thick (Cederstrom et al. 1964) and are from the latest Wisconsinan glaciation. In the Anchorage Lowland, southwest of the cantonment, deposits reach more than 305 m thick. Diamictons from the maximum extent of ice in the past (more than 120 ka BP) probably lie below the Bootlegger Cove Formation, Dishno Pond moraine, and Mountain View fan deposits, but their extent and locations are not known. Diamictons from these events probably have a low permeability and therefore are confining layers that affect ground water conditions beneath the cantonment.

Detailed subsurface geological information is generally absent, except in a few locations (i.e., Turnagain Heights and Lynn Ary Park), where geotechnical studies have been carried out to determine the cause of ground failure during the 1964 earthquake (e.g., S&W 1964, Lade et al. 1988, Updike et al. 1988) or to investigate ground water conditions (e.g., Freethy 1976, Anderson 1977, Dearborn 1977, Munter and Allely 1992). There are also 2281 records in the USARAK's GIS of soil borings and well logs on Fort Richardson, but only 146 reached depths greater than 15 m (Fig. 9). The records from these logs contain general information on engineering properties and material types (e.g., USACE 1996b), but infrequent sampling intervals (2 to 3 m) provide insufficient information for detailed stratigraphic analyses (all logs described in this report are included in Hunter et al. 1997). This is compounded by a lack of consistency in the borehole log descriptions among contractors. To achieve a better understanding of the stratigraphy, we must infer subsurface characteristics from coastal exposures along the Knik Arm and Eagle River, extrapolation from nearby deep wells, limited interpretation of ground-penetrating radar (GPR) profiles, and a reconstruction of the glacial history.

A conceptual stratigraphic model for the can-

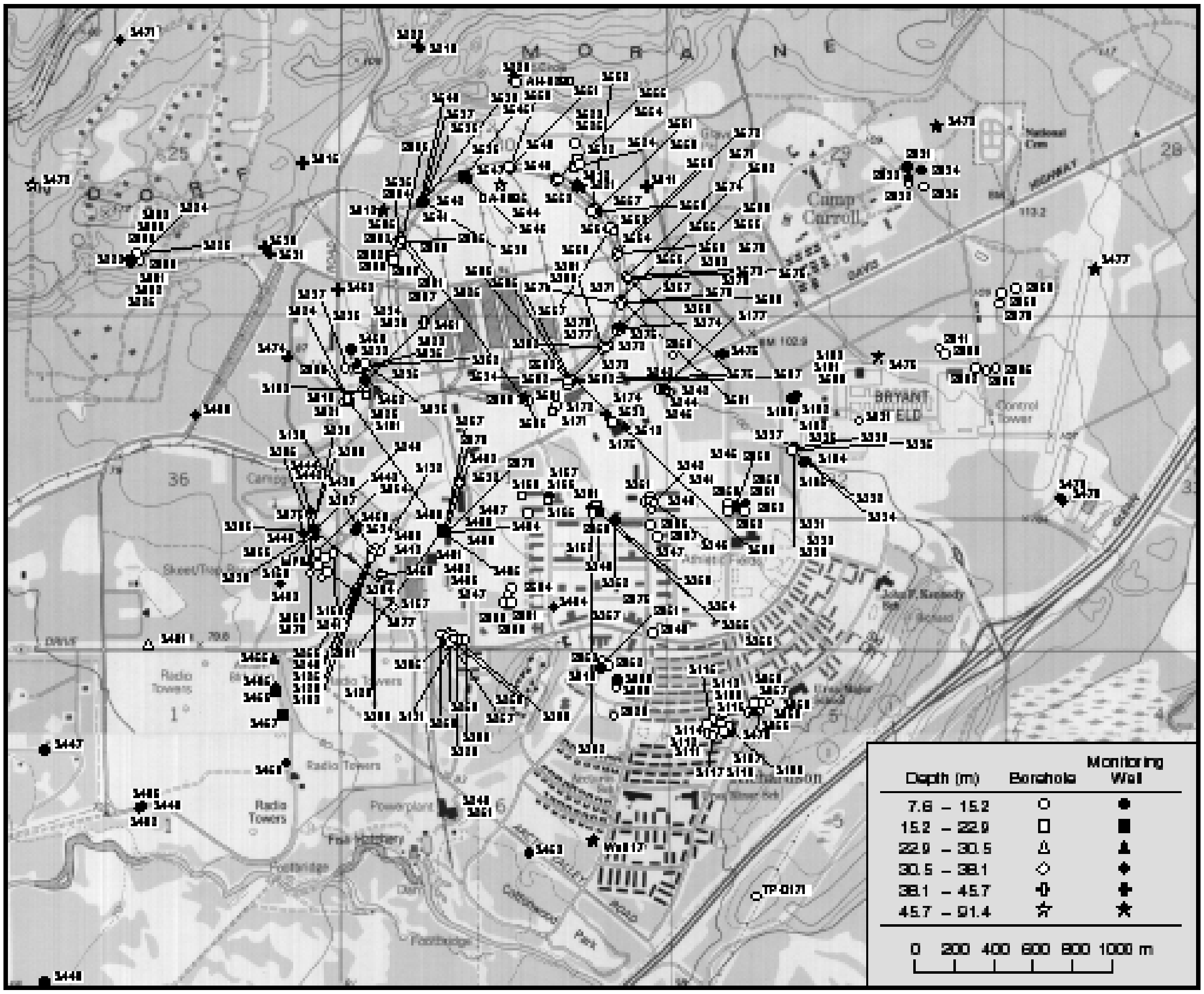



*Figure 9. Boreholes and ground water monitoring wells reaching depths greater than 7.5 m.*

tonment of Fort Richardson, based on the Late Wisconsinan glacial history of the Anchorage Lowland, is shown in Figure 10. Deposits older than Wisconsinan age are ignored because they are poorly documented in the region and more recent glaciations would have likely modified or eroded them away. Therefore, older diamicton deposits are probably limited and may be only locally important in the regional hydrogeology. While the model gives us a theoretical framework for the hydrogeology, it is generalized and does not account for the variability in space and through time that typifies glacial and glacial–marine environments. Nor does it account for the effects of erosion and reworking after the sediments were deposited.

The cycles of ice advance and retreat that the region has experienced would have created a complex stratigraphy below the cantonment (e.g., Fig. 3). For our purposes, we assume that a lower boundary equivalent to the late Wisconsinan ground moraine (a diamicton equivalent to the Rabbit Creek moraines; Plate 1) is located above either pre-Wisconsinan drift or bedrock (Fig. 10). Two diamicton horizons above the Rabbit Creek deposits correspond to glacial advances that we call the Fort Richardson and Dishno Pond readvances. The last advance, which corresponds to the deposition of the Elmendorf Moraine, did not override the cantonment area. Therefore, no diamicton blanket was deposited across the cantonment from this advance. Rather, coarse proglacial and ice marginal outwash deposits likely interfinger with lenses or discontinuous layers of diamicton generated along the front of the Elmendorf Moraine.

Proglacial stratified silt, sand, and gravel were likely deposited between the Fort Richardson and Dishno Pond events, and on the surface generally south of the Elmendorf Moraine (Fig. 10). Ideally,

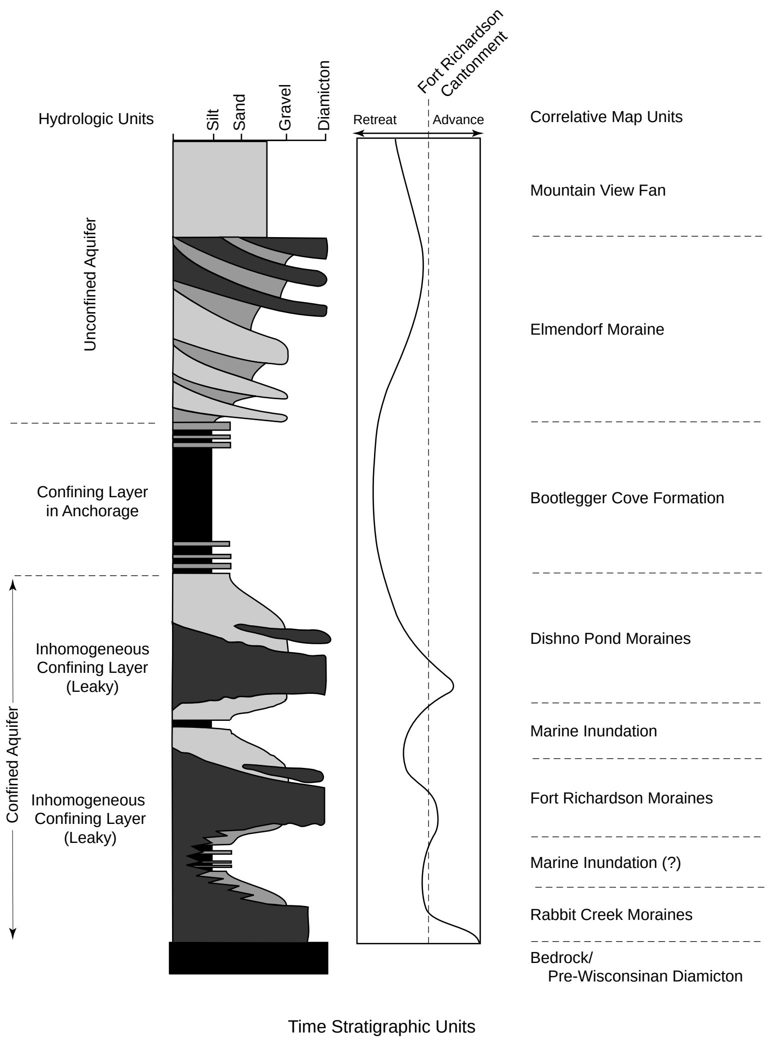



*Figure 10. Conceptual time–stratigraphic model for Fort Richardson below the cantonment area.*

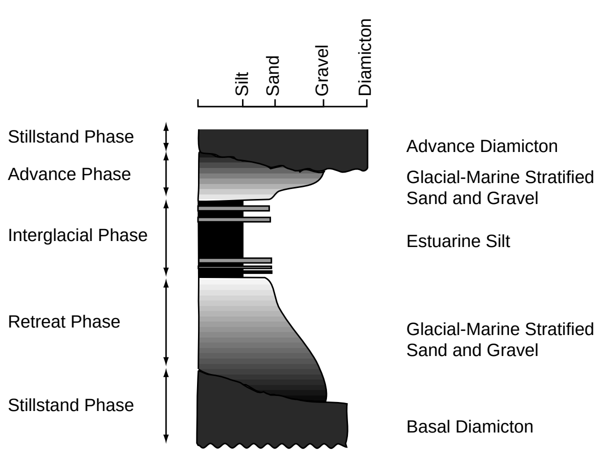



*Figure 11. Conceptual stratigraphic sequence.*

ice retreat and subsequent readvance produce a proglacial stratigraphic sequence consisting of a gravel that fines upward (decreasing millimeter grain size) to thinly laminated silt, followed by a sand that grades upward to a gravel (Fig. 11). The upward fining in the lower portion of the sequence records an increase in distance from the margin as it retreats. This results in an increase in the percentage of sediment deposited from suspension in the sea water (e.g., Dowdeswell and Murray 1990, Cowan and Powell 1990). These silt layers, therefore, are the product of deposition when ice was located closer to the head of Knik Arm. Silt grading upwards to gravel in the upper portion of the sequence records the advance of ice into a marine basin behind a morainal shoal (Post 1975, Mayo 1988). Suspension settling was gradually replaced by sand and gravel deposition from sediment gravity flows (turbidites and debris flows) generated by failures of the submarine moraine as the ice advances. A diamicton (or till) was deposited by the glacier as it overrode the proglacial deposits (e.g., Hunter et al. 1996b). The thickness of the strata, as well as the sedimentary sequence, depend on the rate, extent, and duration of retreat and readvance, the local importance of other sediment sources, and the length of time that the deposits are exposed to subglacial and subaerial processes after they were deposited.

To develop a model of the sedimentary stratigraphy for Fort Richardson, it is thus critical to know the extent of the retreat, as well as the advance, of the Fort Richardson, Dishno Pond, and Elmendorf glaciations. Unfortunately, this is not well known. Schmoll et al. (1996) note that estuarine silt was deposited in the North Fork Campbell Creek and Chester Creek areas following both the Fort Richardson and Dishno Pond retreats. Its presence implies intertidal conditions and marine submergence, but the extent of this submergence up Knik Arm is not known. We assume that the cantonment area was also deglaciated, but probably for a relatively short time.

What happened between the Rabbit Creek and Fort Richardson advances and moraine development is also unknown. Those deposits are deeply buried in the Fort Richardson area. The nature and extent of the Fort Richardson moraines suggest that they probably record a period when the glacier terminus was relatively stable. This condition, a stillstand, might have resulted from local changes in glacier dynamics as the terminus retreated to the mouth of Knik Arm (e.g., stillstands are common at points of valley constriction [Warren and Hulton 1990]). Therefore, it is probable that the cantonment was not deglaciated between the older Rabbit Creek and Fort Richardson stages, and thus subglacial and submarine diamictons were more or less continuously deposited over this time interval.

The best record of glacial activity is associated with the advance of ice that built the Elmendorf Moraine (Elmendorf advance). However, the record of this cycle is not complete below all of Fort Richardson because the Elmendorf advance stopped north of the main cantonment area and, thus, a basal diamicton was only deposited upglacier of the Elmendorf Moraine.

During the Elmendorf advance, marine silt of the Bootlegger Cove Formation was probably eroded and recycled into a moraine shoal as the ice advanced over it. The end of the advance led to the Elmendorf Moraine being deposited through combined glacial (thrusting, pushing, meltout, lodgement), fluvial (outwash streams), and gravitational (debris flows) processes. This produced a complex internal stratigraphy. Interbedded glacioestuarine silts (i.e., Bootlegger Cove Formation), diamictons, gravels, and sands, without a regular lateral or vertical repetitive sequence, is the result. A local example is the exposed sea bluffs at Fire Island near the mouth of Knik Arm (Fig. 3). Any of the fjord bottom sediments in shallow water near the ice margin were probably eroded by waves and coarsened as a result (similar to the Presumpscot Formation in coastal Maine [Bloom 1960]). Close to the Elmendorf Moraine, coarse materials probably compose a significant proportion of the Bootlegger Cove Formation, although this has not been clearly identified.*

The stratigraphy below the cantonment (Fig. 10) consists of several major sedimentary units (listed from oldest to youngest) as follows.

* Personal communication with H.R. Schmoll, USGS, 1996.

**Post-Rabbit-Creek outwash**

This is a well-stratified, moderate- to well-sorted sand and gravel above the Rabbit Creek diamicton or bedrock. The unit is assumed to be variable in thickness, up to a few tens of meters thick, but may locally pinch-out along valley walls. The outwash is unconformably overlain by Fort Richardson diamicton, but pump tests by Cederstrom et al. (1964) demonstrated hydraulic linkage to deposits higher in the sequence. The linkage is probably related to high hydrostatic pressures at depth that drive flow through fractures, faults, and local stratigraphic anisotropies in the overlying diamicton.

**Fort Richardson and Dishno Pond sequences**

Well log records described by Cederstrom et al. (1964) indicate two distinct glacial diamictons buried in the area, while Trainer and Waller (1965) and Schmoll and Barnwell (1984) tell of up to seven glacial horizons. More than 20 diamicton and 10 silt strata were identified in the borehole in Tikishla Park, located about 11 km south of the Elmendorf Moraine (Yehle et al. 1986). However, it is not clear that these represent more than local variations in sedimentary processes and deposition, or movements in the ice margin.

For our generalized model (Fig. 10), we accept the two-drift theory (Cederstrom et al. 1964) because it agrees nicely (although probably coincidentally) with the Fort Richardson and Dishno Pond moraines recognized by surficial mapping programs (e.g., Schmoll et al. 1996). We realize that this is an oversimplification, but suggest that it is reasonable for building our conceptual stratigraphic model, given the current constraints in knowledge of the glacial history and stratigraphy.

Deposits of these advances are hydraulically connected, as demonstrated by Cederstrom et al. (1964), and compose the bulk of the confined aquifer in the Anchorage Lowland. Despite rapid facies changes and broad, laterally continuous diamicton sheets, deposits of these two glacial phases form an extensive aquifer at depth. The sedimentary sequences are detailed below.

*Fort Richardson sequence*

A lower diamicton unconformably overlies the Rabbit Creek outwash. The basal contact is probably erosional, although it should be locally interbedded with gravel. This diamicton is probably stratified, with occasional sand and gravel horizons. Interbedded gravels and diamictons are expected where ice-proximal debris flows, gener-

ated along the grounding line of the tidewater margin, would mix with outwash sand and gravel. Diamicton beds decrease in abundance up-section, as the ice margin receded northwards. Higher in the stratigraphic sequence, gravels would grade to sand and silt. We question whether or not the cantonment area was deglaciated during this time, for the Fort Richardson ice may have halted its retreat at the mouth of Knik Arm. If there was a limited retreat up Knik Arm, then the deposition accompanying it was probably short lived and the deposits thin. The uppermost materials of the Fort Richardson sequence probably consist of coarsening upward sand and gravel as the ice readvanced into the area, this being the Dishno Pond glaciation.

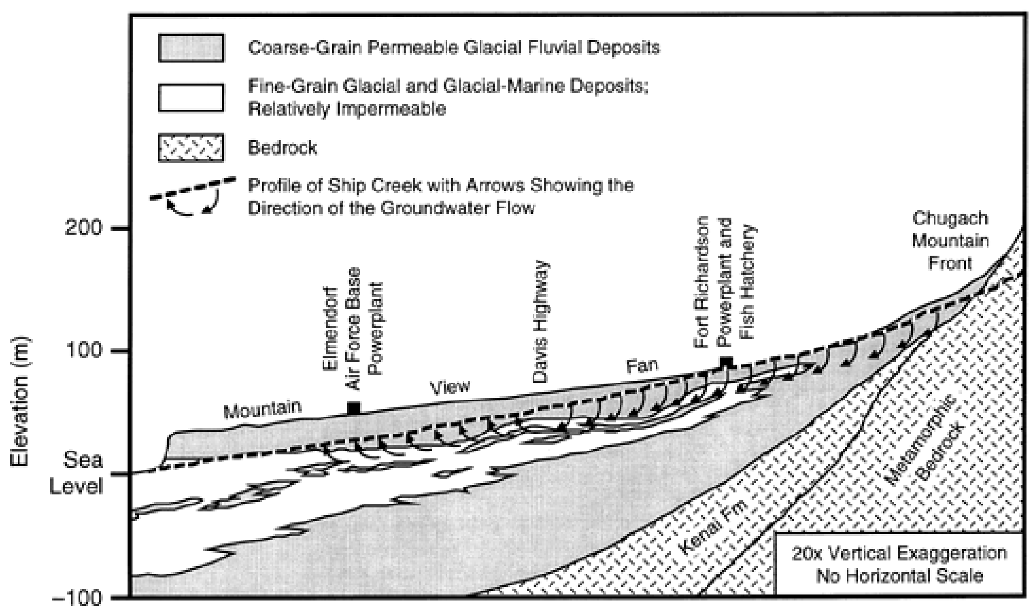
*Dishno Pond sequence*

The Dishno Pond advance produced a broad diamicton (till) sheet that covers much of the Anchorage Lowland (Plate 1). This diamicton unit unconformably overlies the coarsening upward gravel deposited in front of the Dishno Pond advancing ice. The diamicton should be similar to the Fort Richardson diamicton and be a few to tens of meters thick. The upper contact will be interbedded and gradational into gravel deposited during glacial retreat. This gravel grades upward in section into a sandy silt and the silt of the Bootlegger Cove Formation.

**Bootlegger Cove Formation**

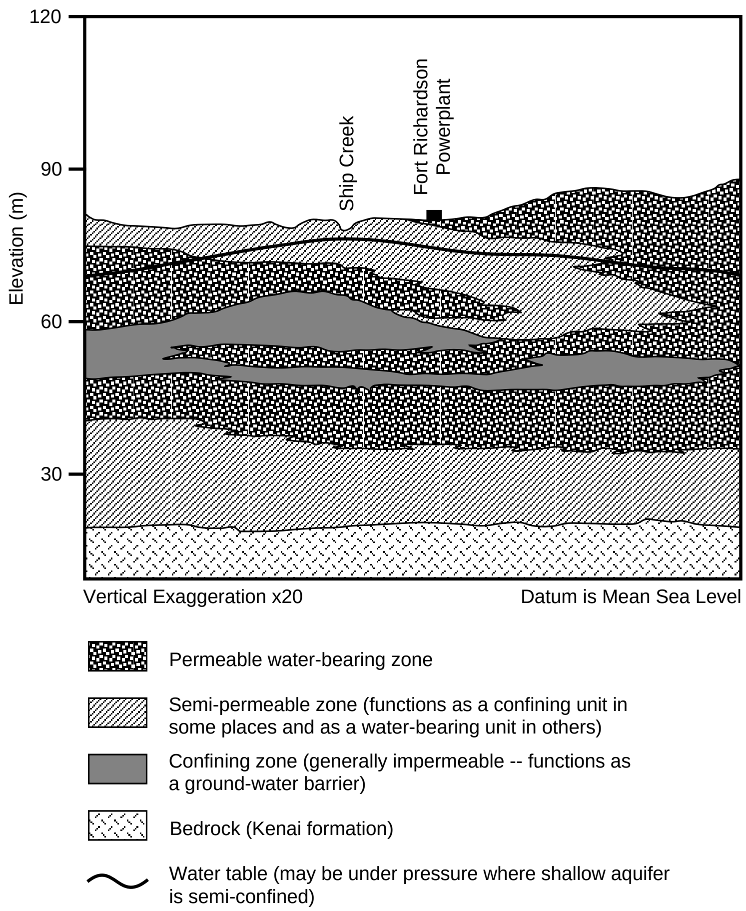
This is a deposit mostly of silt-size material that covers at least 100 km$^2$ in the Anchorage Lowland, where it is an important confining layer in the regional ground water flow system (Cederstrom et al. 1964, Freethy 1976). The unit is usually 30 to 45 m thick, although locally it may exceed 90 m (Cederstrom et al. 1964). The Bootlegger Cove Formation exists below Elmendorf Air Force Base (USAF 1994) and is exposed beneath the Elmendorf Moraine in coastal bluffs of Knik Arm (Miller and Dobrovolny 1959, Cederstrom et al. 1964). Boreholes drilled for ground water investigations near the Fort Richardson powerplant revealed a fine-grained silty horizon that pinched out laterally (Fig. 12) (Freethy 1976, Anderson 1977); however, the northern and eastern limits of this particular horizon are not known. If the northeastern margin of the Bootlegger Cove Formation extends under the cantonment area, it is likely to be sandy and to thin from less than 10 m thick in the south–southwest to nonexistent in the north and east. Such a transitional sandy phase is likely to be more permeable and hydraulically conductive than the lower portions of the Bootlegger Cove Formation common to the southwest.

Well log and ground water records on Fort Richardson attest to the presence of a confining layer that is sometimes assumed to be the Boot-

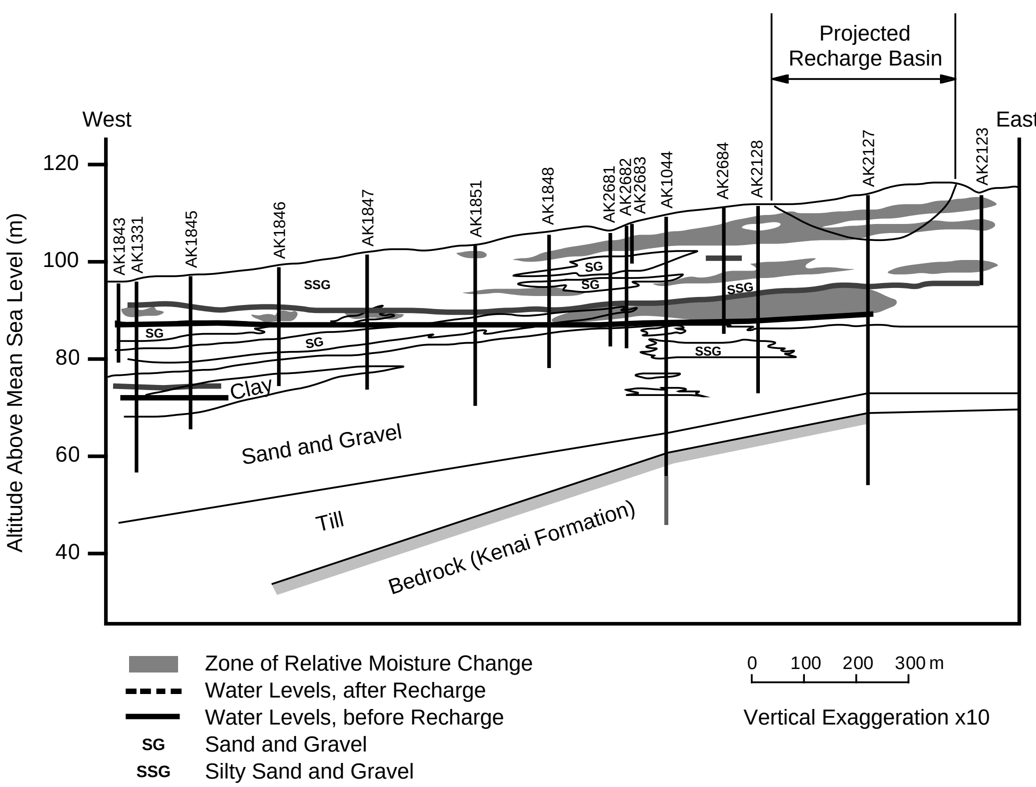



*a. Longitudinal profile showing the northward pinching of the Bootlegger Cove Formation. (After Freethy 1976.)*

*Figure 12. Cross sections along Ship Creek.*




*b. Interfingering relationships of stratigraphic units near the Fort Richardson powerplant along an east–west transect. (After Freethy 1976.)*




*c. Interfingering relationships of stratigraphic units near the Fort Richardson powerplant along a north–south transect. Grey pattern shows moist zones recorded with neutron logs that reflect silt-rich horizons. (After Anderson 1977.)*

*Figure 12 (cont'd). Cross-sections along Ship Creek.*

legger Cove Formation, but available data are not conclusive (Hunter et al. 1997). Descriptions of the confining layer below the cantonment range from till (wells 1 and 17; Cederstrom et al. 1964) to variations of silty gravel, clayey gravel, or silt with sand (e.g., AP-3482, AP-3485) to silt (AP-3468) and clay (AP-3479; USACE 1996b). The majority of these descriptions suggest that they are not all fine-grained, estuarine deposits. Clayey gravel, silty sand, or silt with sand could be interpreted as a nearshore or ice marginal phase of the Bootlegger Cove Formation, but other interpretations are possible, such as diamicton originating as ice marginal debris flows or till. Many of the strata are also laterally discontinuous and therefore probably not the Bootlegger Cove Formation. For example, the 9-m confining layer in well 1 (Cederstrom et al. 1964) at the north side of the railroad yard in the cantonment area does not correlate laterally with deposits in the center of the cantonment, where over 42 m of gravel and sand lies below the surface (well AP-3591, USACE 1996b). The genesis of these deposits needs to be defined by better and more detailed analyses to determine their spatial geometry.

### Mountain View fan

The uppermost stratigraphic unit below the cantonment is the Mountain View fan. Its strata are mostly sand and gravel, with a high concentration (10 to 15%) of fines (silt, clay). Interbedded silty sand and gravel containing lenses and layers of silt and clay are common. Silt and clay horizons may be rafted blocks transported during outburst floods or deposits in small ephemeral ponds and backwater areas of abandoned channels. These fan deposits are commonly on the order of 15 to 18 m thick in the vicinity of the cantonment area (Cederstrom et al. 1964) and are not similar to the mostly “clean” gravel normally associated with glacial outwash.

The fan’s strata may also interfinger with more or less continuous horizons of diamicton where it lies near the margin of the Elmendorf Moraine. Glaciers frequently generate debris flows as sediments are released by melting ice during the moraine building process. These debris flows could have produced diamictons interbedded with silts deposited from meltwater, similar to what is found along the margin of the Matanuska Glacier today (Lawson 1979, 1982). More localized layers or lenses of diamicton may also be generated in meltwater channels incised into the moraine, overall forming a small fan-shaped deposit (Fig. 13; map unit *eo*; Plate 1). Sand and gravel layers

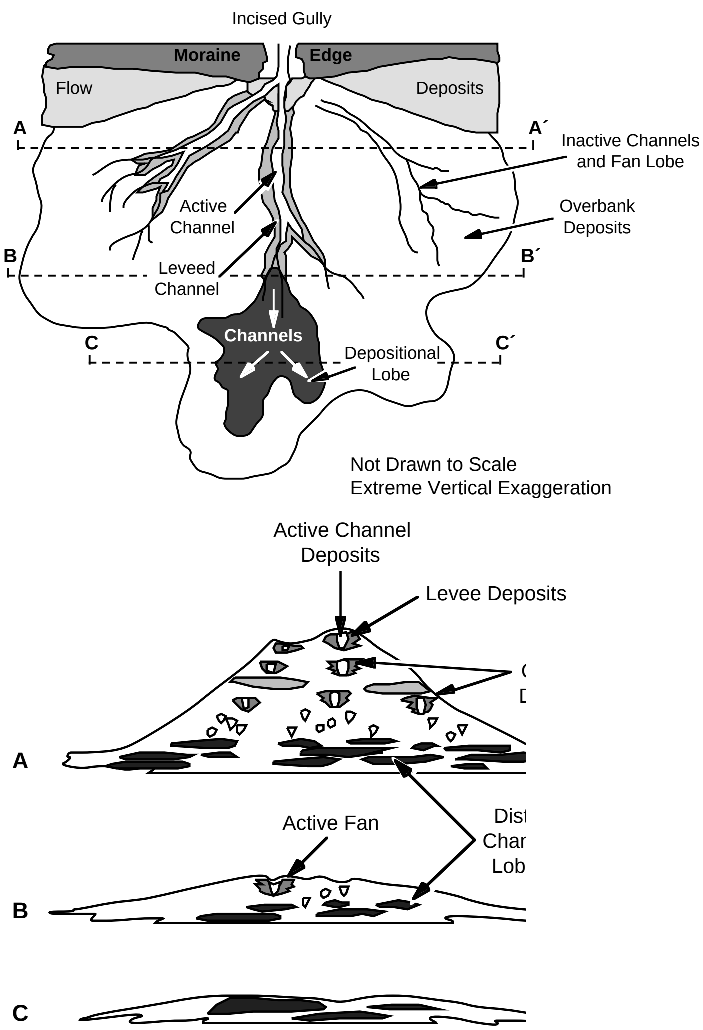



*Figure 13. Fan such as those along the margin of the Elmendorf Moraine. The stratigraphy near the apex is composed of interbedded diamicton sheets and incised channel deposits (gravel). Increased meandering near the fan toe produces broad sand and gravel lenses. (After Galloway and Brown 1973.)*

develop from the normal flow of water in these channels and are interbedded with the debris-flow diamictons (Jopling and MacDonald 1975). Overall, the alternation between debris flow deposition and stream channel migration produces a complex interbedded sequence of gravels and diamictons that probably characterizes the north cantonment area.

## HYDROGEOLOGY

### Regional

The hydrogeology of the Anchorage Lowland has been extensively studied, as researchers have examined various ground water issues (e.g., Cederstrom et al. 1964, Waller 1964, Barnwell et al. 1972, Freethy 1976, Anderson 1977, Zenone and Anderson 1978, Dearborn and Schaefer 1981, Munter and Allely 1992). The overall setting is reasonably well known (Fig. 14). Water enters the ground water system through runoff along the mountain front, percolation of rain and snowmelt across the region, stream infiltration in losing river reaches, and seeps from bedrock fractures (Table 2). The water flows down-gradient (from high hydrostatic head to lower hydrostatic head) in either an unconfined or confined aquifer. The confined aquifer often has artesian water; the potentiometric surface is of higher elevation than the base of the confining layer. Regionally, ground water in the Anchorage Lowland flows roughly from the Chugach Mountains to Knik or Turnagain Arms. It discharges where streambeds intersect the water table (i.e., lower reach of Ship Creek), where the ground water table intersects the surface, forming ponds and lakes, or where the confining layer is truncated (i.e., coastal bluffs), producing seeps and springs.

The hydrogeology in the Anchorage area has traditionally been treated as a three-component system, consisting of an upper unconfined and a lower confined aquifer, separated by a confining horizon with low permeability (Cederstrom et al. 1964, Freethy 1976, Anderson 1977). The silty clay to clayey silt of the Bootlegger Cove Formation is generally thought to be a confining layer because of its low hydraulic conductivity (e.g., USAF 1994). The Bootlegger Cove Formation extends across most of the Anchorage Lowland (Ulrey and Updike 1983), but probably pinches out

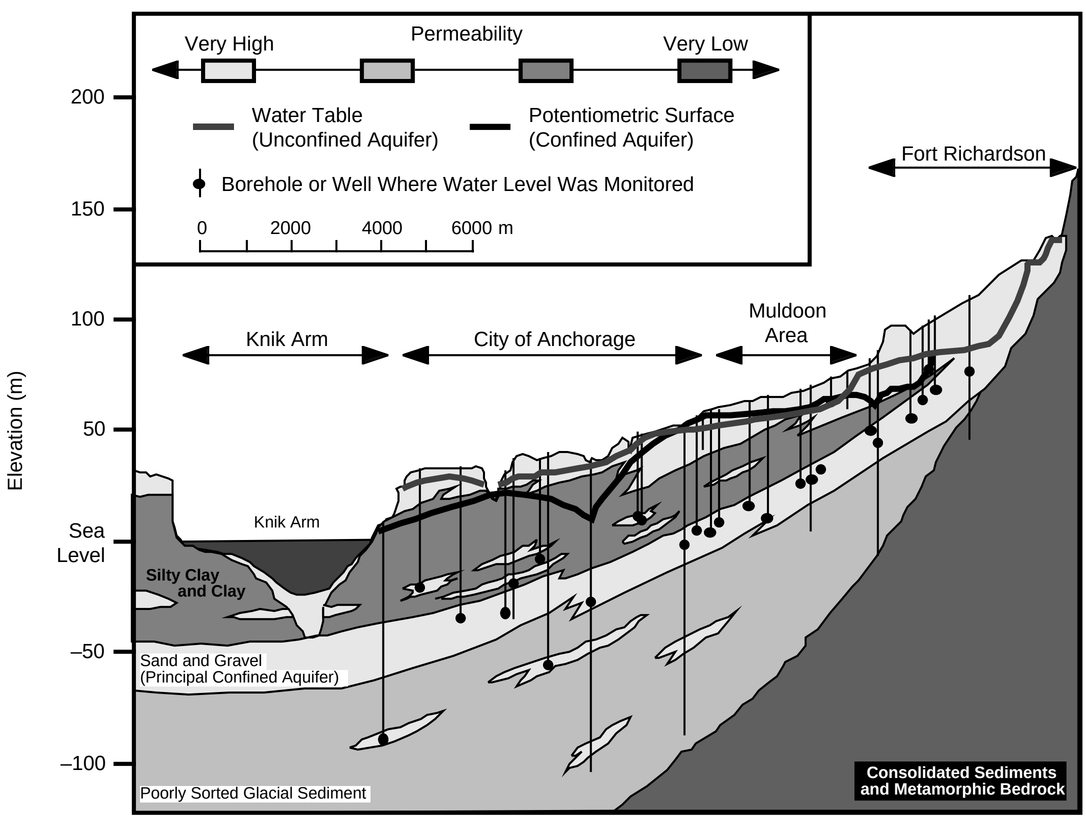



*Figure 14. Generalized hydrogeologic cross section from the Chugach Mountains to Knik Arm. (After Barnwell et al. 1972.)*

somewhere below Fort Richardson. Confining layers appear to exist at the north and southeastern sections of the cantonment, but well AP-3591 found no confining layer in the center of the cantonment, where the confined and unconfined aquifers appear to converge (USACE 1996b).

Sand and gravel of the unconfined and confined aquifers are exceptionally permeable and hydraulically conductive. Recharge studies were conducted by temporarily diverting the flow of Ship Creek into storage basins on Fort Richardson. The recharge rate was measured at $1.5 \times 10^4$ $m^3/day$, while a second test in coarser gravel achieved a recharge rate of $5.3 \times 10^4$ $m^3/day$ (Anderson 1977, Updike et al. 1984). Anderson (1977) calculated a permeability of 68.6 m/day, while Freethy (1976) proposed a much higher value of 720 $m^2/day$ for transmissivity. The ground water mounded during the second test, equivalent to 9.4 and 4.9 m in the unconfined and confined aquifers, respectively (Anderson 1977); however, water levels dropped rapidly once the artificial recharge was shut off.

**Fort Richardson hydrogeology**

The hydrogeology of Fort Richardson has been briefly summarized in numerous engineering reports, but detailed studies are restricted largely to Freethy (1976), Anderson (1977), and USACE (1996b). Despite these studies, the ground water conditions below Fort Richardson remain poorly known and require further detailed investigations. Detailed subsurface information is generally lacking for the glacial sediments that range from 70 to 97 m thick below the cantonment (Cederstrom et al. 1964).

The shallow, near-surface aquifer occurs in the Mountain View fan sediments (Fig. 10 and 12). The water table lies at a depth of 3 to 13 m in sediments that are approximately 18.3 m thick in the main cantonment (Cederstrom et al. 1964, USACE 1996b). The water table dips to almost 37 m bgs (below ground surface) at AP-3462, beyond the apparent limit of the confining layer where the confined and unconfined aquifers converge (Fig. 14 and 15a). The confining layer may be the Dishno Pond or Fort Richardson diamicton or possi-

*a. Top of unconfined aquifer in May 1995. (After USACE 1996b.)*

*Figure 15. Ground water maps. (Contours in feet, as originally measured. To convert to meters, multiply by 0.3048.)*



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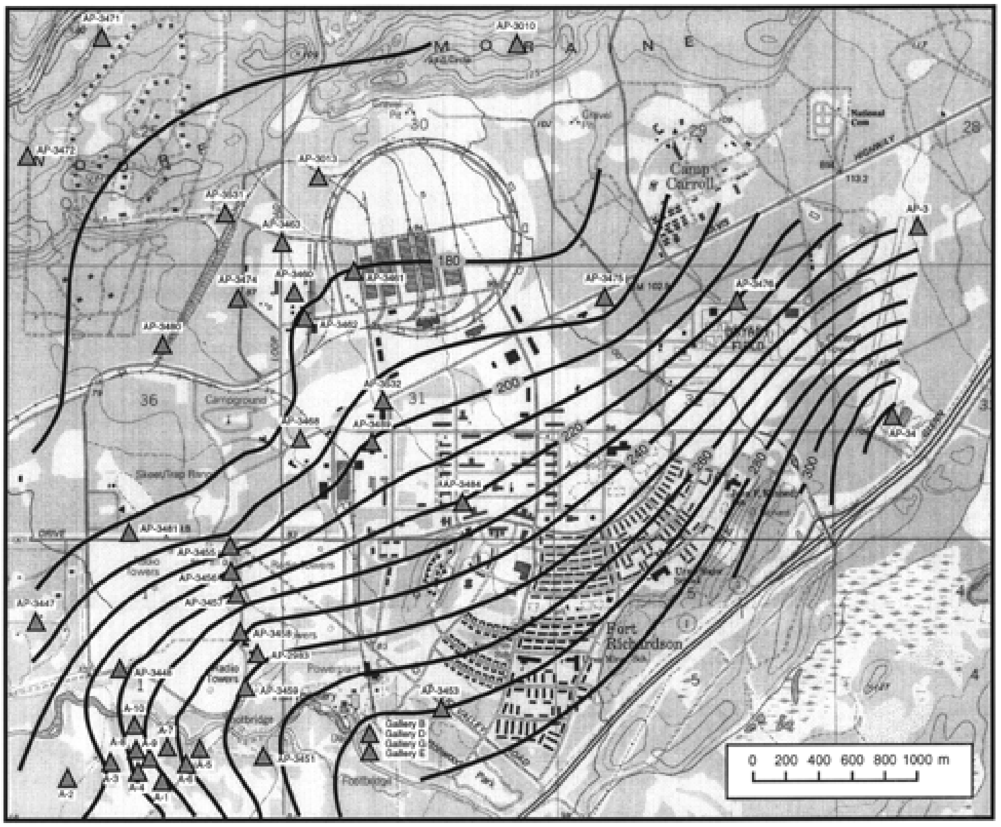
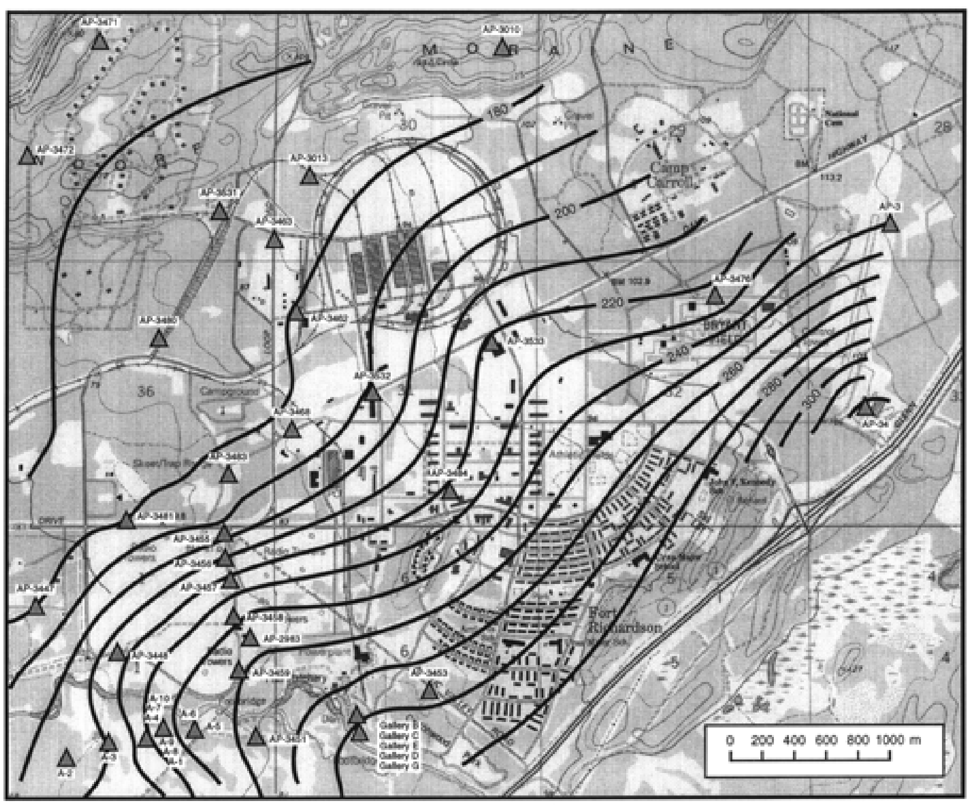




*b. Top of unconfined aquifer in August 1995. (After USACE 1996b.)*





*c. Top of unconfined aquifer in November 1995. (After USACE 1996b.)*

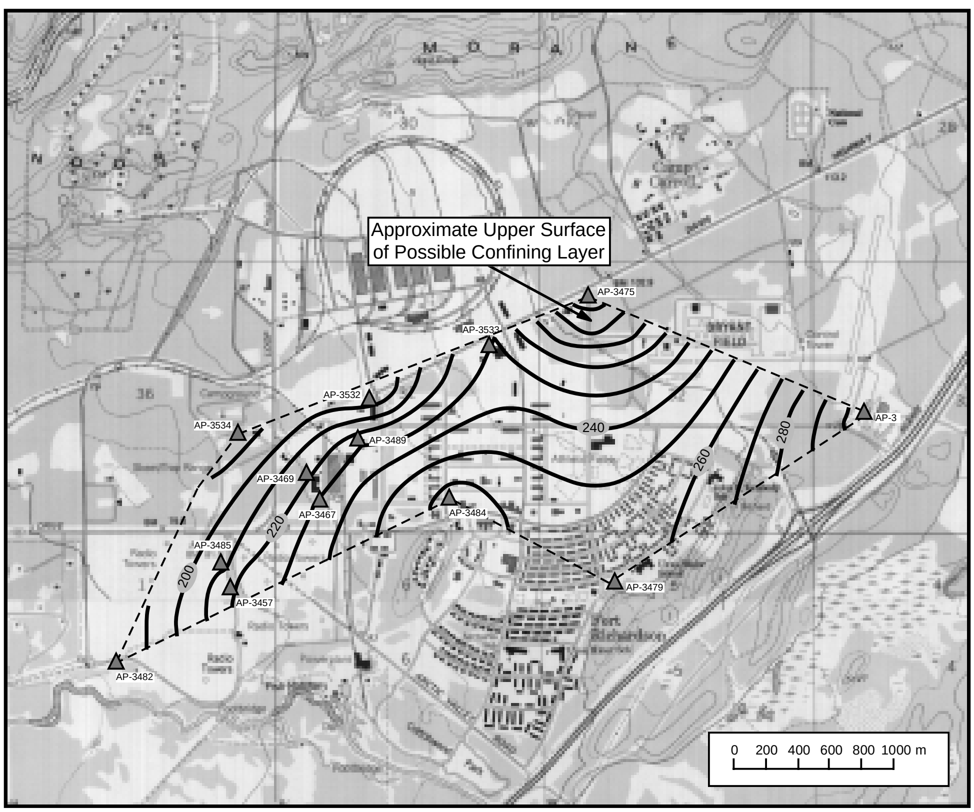
*Figure 15 (cont'd). Ground water maps.*

*d. Potentiometric surface of confined aquifer in May 1995. (After USACE 1996b.)*

*e. Potentiometric surface of confined aquifer in August 1995. (After USACE 1996b.)*

*Figure 15 (cont'd).*

*f. Potentiometric surface of confined aquifer in November 1995. (After USACE 1996b.)*




*g. Top of confining layer as defined by USACE (1996b).*

*Figure 15 (cont'd). Ground water maps.*

bly the Bootlegger Cove Formation. A deep well drilled at the northern edge of the cantonment (well 1; Cederstrom et al. 1964) penetrated about 97 m of unconsolidated sediment prior to encountering bedrock. The upper 15.2 m, with its base at elevation 83 m asl (above sea level), consisted of sandy gravel in Mountain View fan deposits. The next 40 m (base at 43 m asl) was described by Cederstrom et al. (1964) as till; however, the properties of this horizon could also be attributable to a glacial-marine silt.

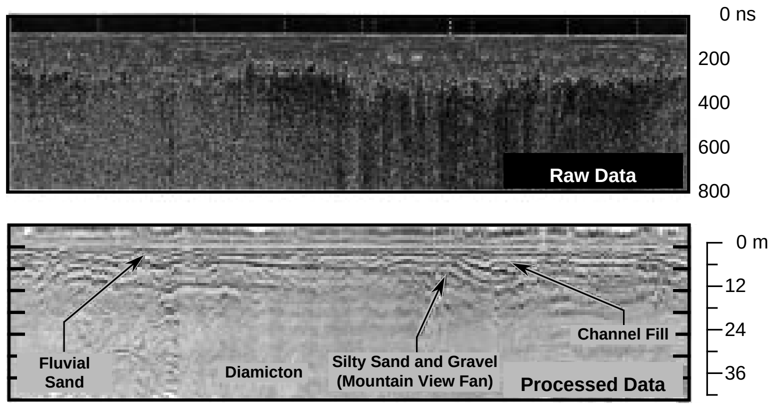



*Figure 16. 50-MHz radar profile collected along Loop Road showing a shallow, gently dipping reflector at the interpreted base of Mountain View fan.*

The USACE (1996b) defined the top of the unconfined aquifer at 52 to 55 m asl, at what would be almost 30 m within this diamicton. A diamicton was also encountered 4 m below the surface (85 m asl) near the Fort Richardson powerplant (well 17; Cederstrom et al. 1964). This diamicton was interbedded with sand and gravel down to 17 m depth (61 m asl). Hills nearby this well site have been mapped as drumlinized ground moraine of Dishno Pond age (Plate 1; App. A). These hills are relict landforms that project through deposits of the Mountain View fan and this may be a lateral extension of the diamicton in the powerplant area.

The the two diamicton horizons in wells 1 and 17 (Cederstrom et al. 1964) top out at approximately the same elevation (83 to 85 m asl), which might suggest that a more or less continuous sheet of diamicton once extended below the cantonment. However, at the southern edge of the railyard loop, AP-3591 penetrated 46 m of gravel down to 50 m asl (Fig. 9). Although its silt content increased at depth, a diamicton was not encountered. We must assume that the confining layer does not exist here. Nearby, wells AP-3184 and AP-3470 encounter perched or unconfined ground water at 96 to 98 m asl, respectively. This is 12 to 15 m above the diamicton in wells 1 and 17. Unfortunately, these wells did not penetrate through the impermeable confining layer (at AP-3184, drilling was stopped just after ground water was encountered), and so we cannot determine the thickness of the diamicton or whether the lower diamicton extends across the area.

Ground-penetrating radar profiles along Arctic Valley Road near here show a strong reflector between 5 and 10 m below the surface that appears to extend to Davis Highway and Loop Road, where a similar reflector dips to a depth of 20 m (Fig. 16) (Strasser et al. 1996). The signal is probably lost below the horizon through attenuation in the silty matrix of the confining layer. The overlying 10 to 20 m of sediment is sand and gravel of the Mountain View fan. Again, this horizon roughly agrees in elevation with the top of the diamicton at well 17 and may be the top of a once-continuous diamicton bed. This stratum may be absent at well AP-3591 because of local dissection during flooding on the fan. Also, proglacial streams migrating across the front of the advancing Elmendorf ice may have eroded and dissecated the sediments. Therefore, the perched ground water zones encountered in wells could simply be locally confined by remnants of the diamicton (Fig. 17a). At places where the diamicton has been eroded, a gravel aquifer extends to great depth (e.g., AP-3591). If the diamicton was actually continuously eroded along the front of the moraine, then the location of the dipping water surface near the Davis Highway and Loop Road (Fig. 15a) could be its northern limit.

Another plausible alternative is that the diamicton observed in well 1 formed as a result of debris flows from the Elmendorf Moraine. Evidence, such as erosional features (clay rip-up clasts) at the base of the diamicton, supports this concept, as do observations along modern glacier margins. The silty deposits may be a transitional phase of the Bootlegger Cove Formation, with the clay balls being recycled material from marine silty clay eroded to the north. If this is the case, the diamicton encountered in well 17 is from a separate source and would either have to dip to the north and west underneath the cantonment,

Figure 17. Proposed stratigraphy below the Fort Richardson cantonment. Erosive activity (a) during deposition of the Mountain View fan cut through the Dishno Pond ground moraine and edges of the Elmendorff Moraine. Erosion and deposition (b) associated with the Mountain View fan was accompanied by sediment failure along the margin of the Elmendorf Moraine, producing an interstratification between sand and gravel and diamicton. Wells drilled at site A would encounter a diamicton at an elevation roughly equivalent to the top of the diamicton encountered in well B.

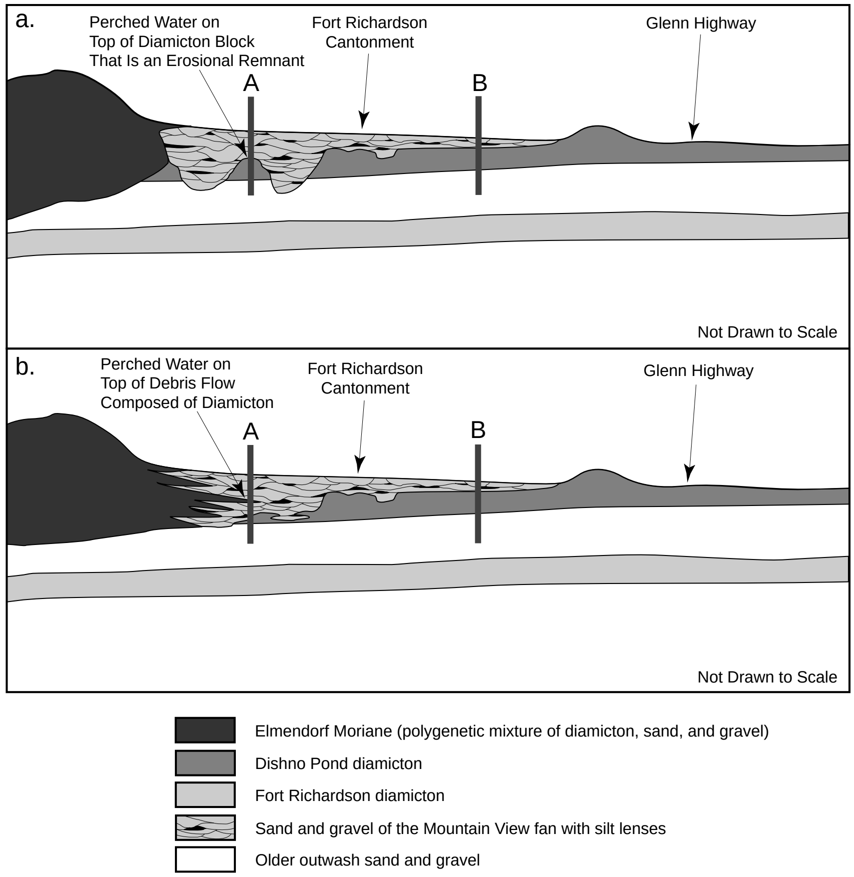



Figure 18. Ground water level at Elmendorff Air Force Base in September 1993. (Contours in feet, as originally measured. To convert to meters, multiply by 0.3048.) (After USAF 1994.)

Elmendorf Moraine, and Bootlegger Cove Formation or it has been eroded away. However, a dipping horizon like this is not supported by our interpretation of the GPR data (Fig. 16).

A more likely alternative is that cantonment deposits result from a combination of these two scenarios, where the diamicton sheet to the south was eroded by proglacial streams in front of the Elmendorf Moraine (Fig. 17b) or dips to the north. Stream and fan deposits shed off of the moraine interfinger with gravel deposits in the fan. Blocks of relict diamicton may be locally buried in the gravel sequence, producing a complex architecture of interbedded diamicton and silty outwash deposits.

The U.S. Army Engineer District, Alaska (USACE 1996b), monitored 43 wells between 1994 and 1995, providing the first detailed look at ground water conditions in the cantonment area on Fort Richardson. These data are augmented by site-specific ground water data related to environmental investigations (E & E 1996, ESE 1991). These preliminary data allow us to begin assessing ground water movement and contaminant transport issues.

Ground water maps (Fig. 15a–c) (USACE 1996b) and data from recent ground water investigations on Elmendorf Air Force Base (USAF 1994) (Fig. 18) allow us to compare these recent results to the model proposed by Freethy (1976) (Fig. 19). Flow lines on Figure 20 show convergent flow in the vicinity of the cantonment area, implying a flow boundary to the north, below the crest of the Elmendorf Moraine. This pattern was not supported by the USACE (1996b) report. The ground water maps produced by the Alaska District imply that the surface of the unconfined aquifer was dipping below the distal edge of the moraine (wells AP-3471 and AP-3472; Fig. 15a–c). This area is, however, located at the outer limit of the USACE data and is therefore poorly defined. Figure 20 compares the contrasting flow lines from the two models along the north edge of the cantonment. We cannot resolve this discrepancy,

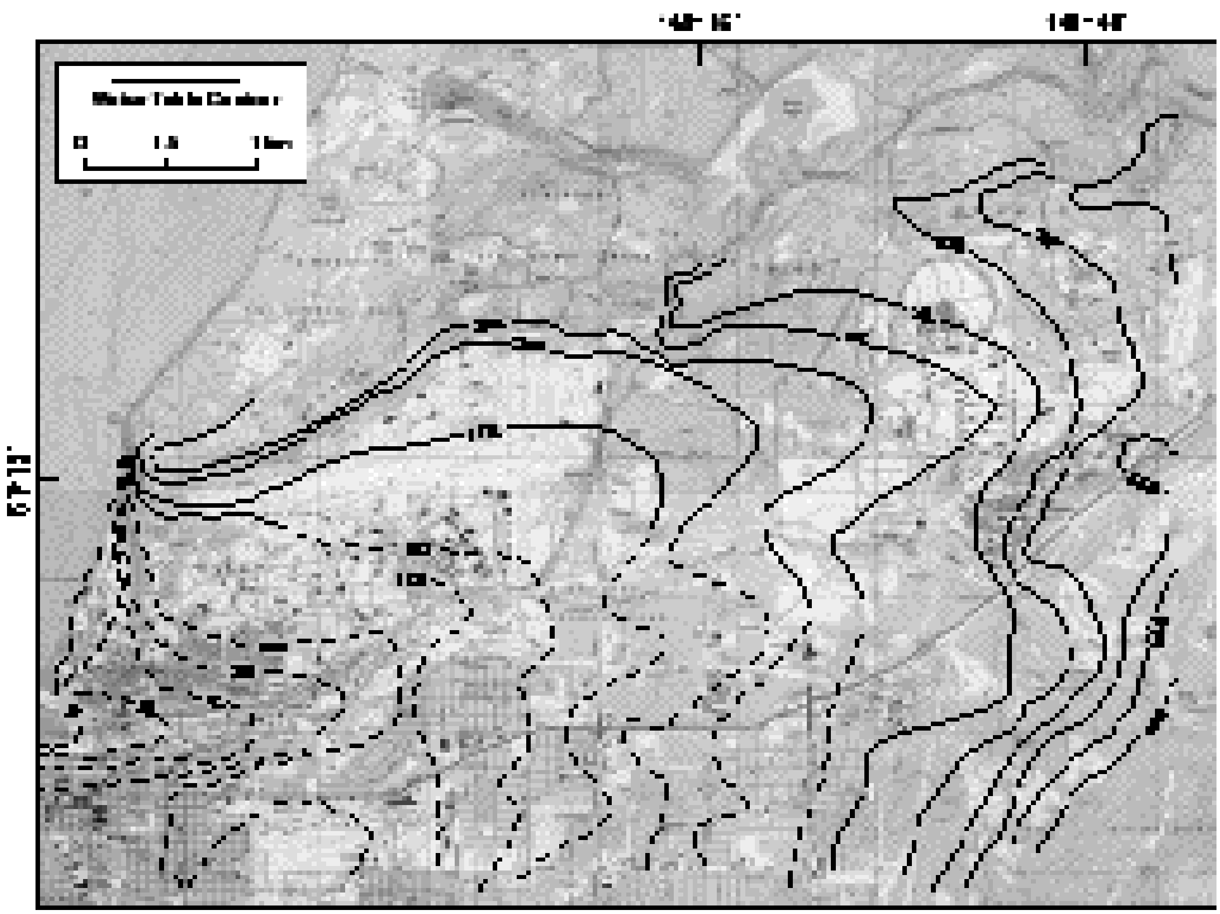


*Figure 19. Ground water level in the lower Ship Creek basin as determined by Freethy (1976). (Contours in feet, as originally measured. To convert to meters, multiply by 0.3048.)*



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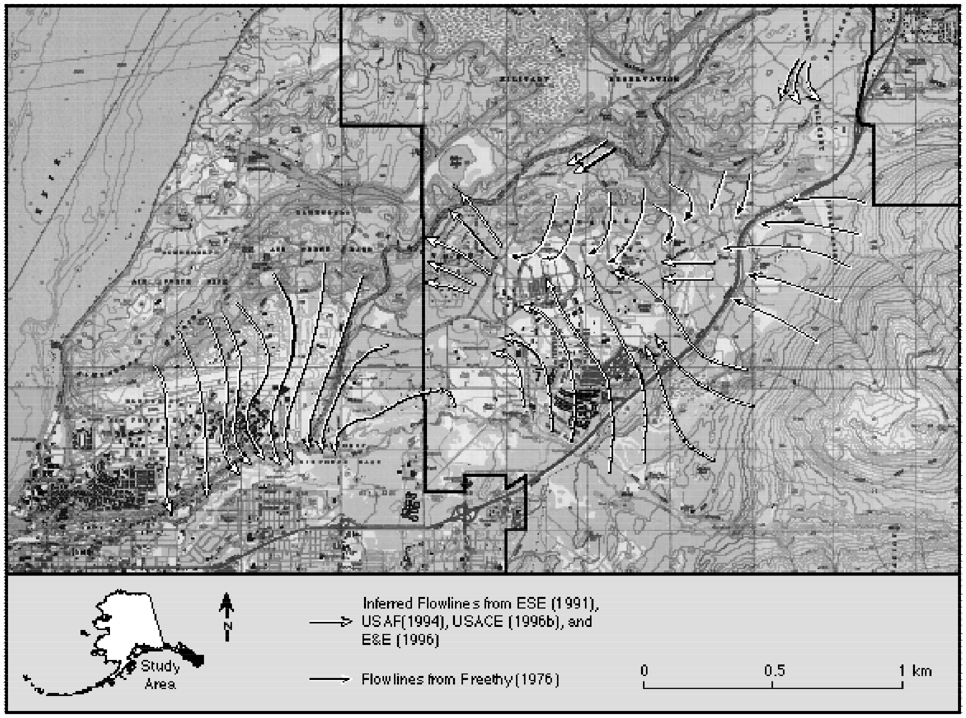


*Figure 20. Comparison of ground water flow patterns. White flow arrows are inferred from ESE (1991), USAF (1994), USACE (1996b), and E&E (1996). Black flow arrows are from Freethy (1976).*

but it is clearly important to understanding how ground water moves and contaminants migrate in the cantonment area and Operable Unit D (OU D).

The elevation of the water table (unconfined aquifer) was monitored three times in 1995 and used to contour the water surface below the cantonment area (Fig. 15). Some interesting changes in the configuration of the water table and associated flow paths took place. Generalized flow patterns during each of these periods (May, August, November) were to the northwest, reflecting recharge from Ship Creek. During relative low flow (low recharge) conditions in May, there appears to be a strong divergence in flow near the intersection of the Davis Highway and Loop Road. The divergence is probably controlled by the upper topography of a confining layer. There may also be flow divergence caused by a zone of high hydraulic conductivity below the Mountain View fan deposits in the vicinity just west of Loop Road. In August, under higher recharge conditions, flow lines are still divergent but tend to form broad arcs that are more consistent and subparallel, with discharge towards the north just east of the railyard loop and westerly near Loop Road.

One problem that we have observed is that the top of the confining layer, as defined by the Corps (USACE 1996b), is found at a shallower depth than the unconfined aquifer (Fig. 15a–c, g). Although this appears to be a product of the boundaries chosen for contouring, it introduces serious implications to future modeling, since this situation cannot exist in nature. Further investigation is needed to resolve this issue, especially since it directly affects the modeling of contaminant transport in OU D (ENSR 1996).

Monitoring of the confining aquifer during the same period shows a general tendency for northwesterly flow (Fig. 15d–f). Along a line from AP-3479 to the north side of Building 740 (approximately parallel to flow), the gradient of the potentiometric surface was approximately 0.0155 for all measurement periods. The 61- and 76-m contours almost replicate those proposed by Cederstrom et al. (1964). There appears to be only minimal seasonal or long-term change in the confined aquifer.

Data indicate that along the northwest edge of the cantonment, the unconfined aquifer plunges and recharges a deeper aquifer (Fig. 15a). Based on the ground water data from AP-3471 and AP-3472 (USACE 1996b), it appears likely that at least some of this water reenters a confined aquifer and continues flowing to the northwest underneath the Elmendorf Moraine. More data are

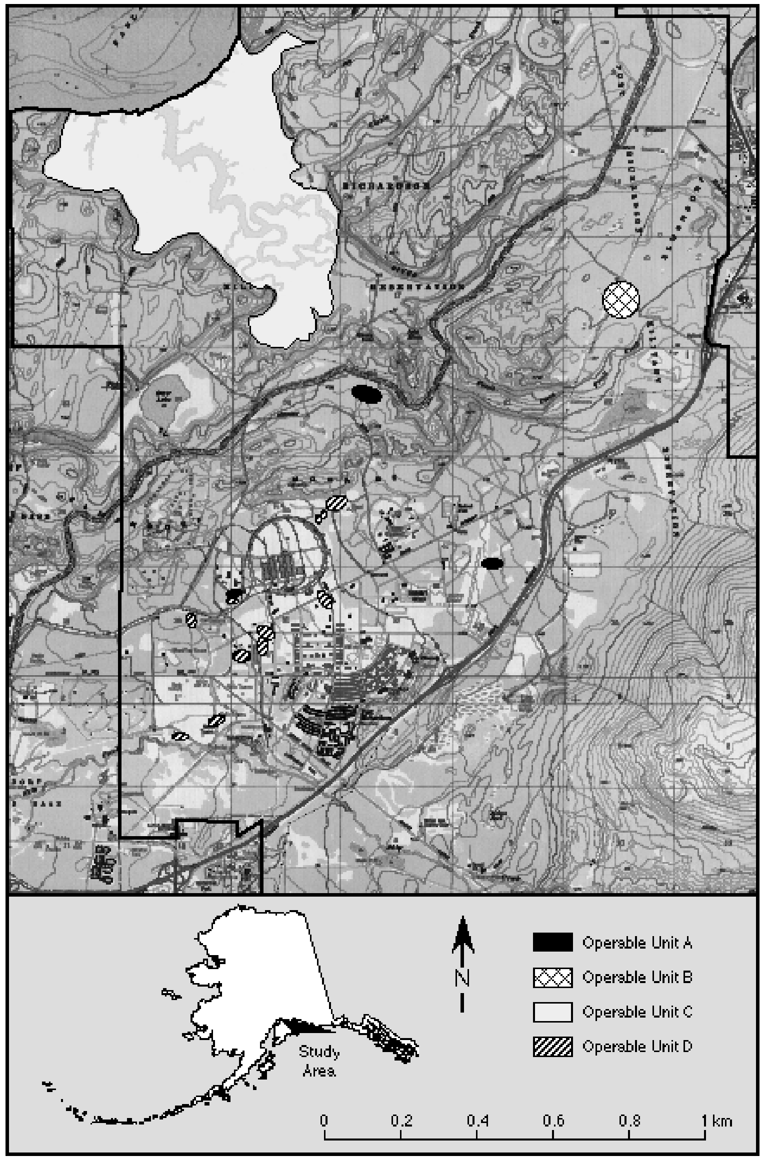


*Figure 21. Operable Units on Fort Richardson.*

required however to determine if in fact this is happening and how it affects flow in general.

**Significance to contaminant transport**

Based on the limited preliminary data that are available, we can begin assessing contaminant transport in the cantonment area and beneath the different OUs (Fig. 21, Table 3) (USACE 1996a).

*Operable Unit A*

The Petroleum, Oil, and Lubricant Laboratory Dry Well (POLLDW), Ruff Road Fire Training Area (RRFTA), and Roosevelt Road Transmitter Site Leachfield (RRTSL) are in OU A.

The POLLDW is located in a central part of the Mountain View fan deposits, where ground water is relatively deep, about 61 m below the ground surface, or 52 to 55 m asl. Flow vectors fluctuated from roughly north–northwest to almost westerly during 1995 (USACE 1996b). Mean flow is probably to the northwest, but at peak discharge the flow is in a north–northwest direction. In a worst-case scenario, Diesel Range Organics (DRO) at the site could be transported to this deep unconfined aquifer, producing a broad plume at depth. Maximum transport would probably occur during peak ground water discharge, extending the plume to the north–northwest.

Ground water at RRFTA is encountered 46 m below the surface where flow is roughly to the west–northwest (Fig. 22) (E&E 1996). We determined this flow direction on the basis of the site investigation of E&E (1996), but it does not agree with the surface contours determined from data that the USACE (1996b) measured. However, on

**Table 3. Identified or suspected contaminants at Fort Richardson, Alaska.**

| *Operable unit* | *Source area* | *Contaminants* |
|---|---|---|
| A | Building 986 Petroleum, Oil, and Lubricant Laboratory Dry Well | POLs, solvents, semi-volatile organics, and metals |
| | Roosevelt Road Transmitter Site Leachfield | PCBs, solvents, and metals |
| | Ruff Road Fire Training Area | POLs and dioxins |
| B | Poleline Road Disposal Area | VOCs, chemical warefare materials |
| C | Eagle River Flats | White phosphorus |
| D | Building 35-752 | PCBs, diesel, alcohols, paint waste, petroleum hydrocarbons, and dry-cleaning solvents |
| | Building 700/718 | PCBs, POLs, solvents, mineral spirits, alcohols, ethylene glycol, Stoddard solvent, MEK, cyclohexylamine, PCE, and TCE |
| | Building 704 | POLs, chlorinated solvents, alcohols, mineral spirits, paint waste, and ballast water |
| | Building 726 | PCE, TCE, Stoddard solvent and other chlorinated solvents |
| | Building 796 | Battery acid and lead |
| | Building 955 | PCBs, petroleum hydrocarbons, VOCs, semi-VOCs, ethlyene glycol, metals, and pesticides |
| | Building 45-590 | Petroleum hydrocarbons and PCE |
| | Dust Palliative Areas | PCBs, petroleum hydrocarbons, and metals |
| | Landfill Former Fire Training Area | POLs and VOCs |
| | Landfill Grease Pits | POLs, solvents, ethylene glycol, paint waste, and pesticides |
| | Stormwater Drainage Outfall to Ship Creek | Any hazardous substance used at Fort Richardson |

MEK = Methyl ethyl ketone
PCBs = Polychlorinalted biphenyls
PCE = Tetrachloroethylene
POLs = Petroleum, oil, and lubricants
TCE = Trichloroethene
VOCs = Volatile organic compounds

the basis of the investigation by E&E (1996), flow paths appear relatively uniform, so that a plume from point sources should be long and drawn out along ground water flow lines.

A similar situation should be expected at the RRTSL, where flow is to the west–southwest and ground water is 24 m below the surface (Fig. 23). However, modeling by E&E (1996) suggests that DRO-type contaminants are unlikely to migrate into the ground water at these depths for 90 years or more.

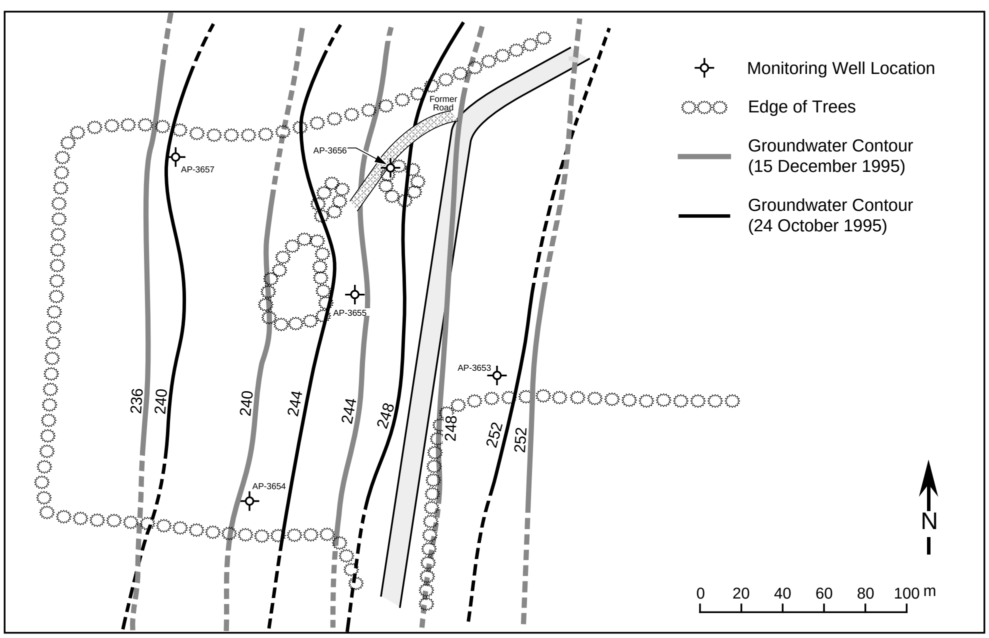


*Figure 22. Ground water level at RRFTA as monitored by E&E (1996). (Contours in feet, as originally measured. To convert to meters, multiply by 0.3048.)*



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*Figure 23. Ground water level at RRTSL as monitored by E&E (1996). (Contours in feet, as originally measured. To convert to meters, multiply by 0.3048.)*

*Operable Unit B*

The Poleline Road investigation report (ESE 1991, OHM 1994) shows divergent flow below this contaminant site (Fig. 24). The area west of Poleline Road appears to experience south–southwesterly flow, with an increasingly easterly component further to the east. A plume generated in this area would likely spread out along the flow lines.

*Operable Unit C*

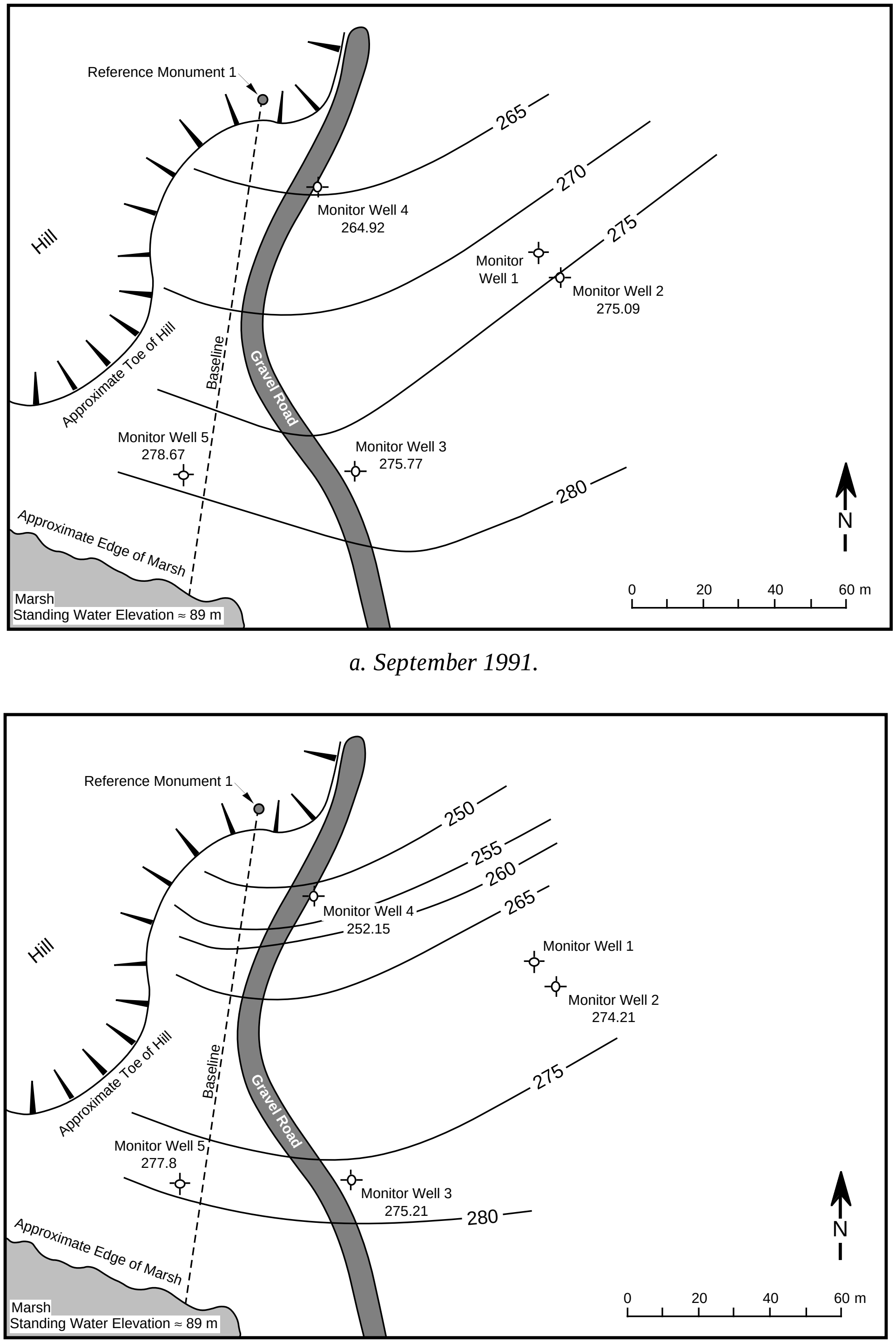
Only limited, very shallow ground water data are available for ERF (Racine and Cate 1995). The contaminant being investigated is elemental white phosphorus, which is restricted to the surface and near-surface environment. It is relatively insoluble and transport appears limited to surficial drainageways and the Eagle River (Lawson et al. 1996a,b).

*Operable Unit D*

The numerous OU D sources can be separated into three general clusters as shown on Figure 21. To the south, the Stormwater Outfall and Building 35-752 overlie deposits of the Ship Creek drainage. Along this section of Ship Creek, stream waters recharge the aquifer system and the water table is very shallow (approximately 5 m bgs near Building 35-732). Ground water flow lines at these sites trend from west–northwest to northwest.

A second group of source areas in the cantonment lies near the central portion of the Mountain View fan deposits, including Buildings 45-590, 955, 726, 700 / 718, 704, and 796. The ground water flow at Building 955 is similar to that described for the POLLDW of OU A. At Building 796, located northeast of most of this group, ground water is encountered at about 30 m bgs. Ground water flow ranges from northerly to northwesterly (Fig. 15a–c). This variability would produce a broad plume if pollutants were to migrate to this deep level. The remainder of the group (Buildings 45-590, 726, 700 / 718, and 704) are relatively close together in an area where the water table is encountered at about 33 m below the surface. The ground water flow lines in this area trend fairly consistently to the northwest, which would produce a plume with limited lateral dispersal.

The third group of OU D sources lies at the northern edge of the Mountain View fan in the landfill area (Landfill Grease Pits, Landfill Former Fire Training Area). These sites are close to the southern edge of the Elmendorf Moraine and the underlying materials should include an interfingering of moraine- and fan-related deposits. The ground water surface in this region was encountered at a depth of 46 m. These sites are at the perimeter of the region contoured by the USACE (1996b) ground water study, where extrapolation may have resulted in unreliable values. The flow directions shown range from




*a. September 1991.*



*b. October 1990.*

*Figure 24. Ground water level at Poleline Road as monitored by ESE (1991). (Contours in feet, as originally measured. To convert to meters, multiply by 0.3048.)*

westerly in May and August to north–northwest in November. Contaminants reaching the ground water table in this region would form a broad plume.

## CONCLUSIONS

The hydrogeology of Fort Richardson is far more complicated than that of Anchorage and neighboring Elmendorf Air Force Base. Defining the boundary conditions is particularly difficult. In both of the other areas, the Bootlegger Cove Formation forms a relatively continuous blanket that behaves as a flow boundary to the upper unconfined aquifer. Flow across Elmendorf Air Force Base is generally north to south (Fig. 18 and 20), with ground water recharge from the Elmendorf Moraine and discharge to the lower reaches of Ship Creek. Therefore, both the Elmendorf Moraine and Ship Creek can be treated as flow divides (north and south, respectively). To the east, flow circulates counter-clockwise in the vicinity where Ship Creek shifts from a losing stream (where it recharges the aquifer) to a gaining stream (where the aquifer discharges into the stream; Fig. 25). USAF (1994) treats the Bootlegger Cove Formation as a boundary to the west, where it reportedly rises below the coastal bluffs and limits westerly flow.

Ground water surface maps currently propose conflicting models for Fort Richardson (Fig. 20). According to Freethy (1976), the crest of the Elmendorf Moraine acts as a flow divide and causes convergent flow below the northern area of the cantonment along the front of the moraine. The unconfined aquifer mimics surface topography and flows from the high elevations along the Elmendorf Moraine and the front of the Chugach Mountains. Below the cantonment, these topographically driven flows encounter water moving north in response to recharge from Ship Creek. Flow convergence would produce a westerly flow in the unconfined aquifer and high discharge along the front of the Elmendorf Moraine towards Elmendorf Air Force Base. However, because the unconfined aquifer plunges northward below the cantonment, this flow instead probably recharges the deeper confined aquifer beyond the eastern limit of the Bootlegger Cove Formation.

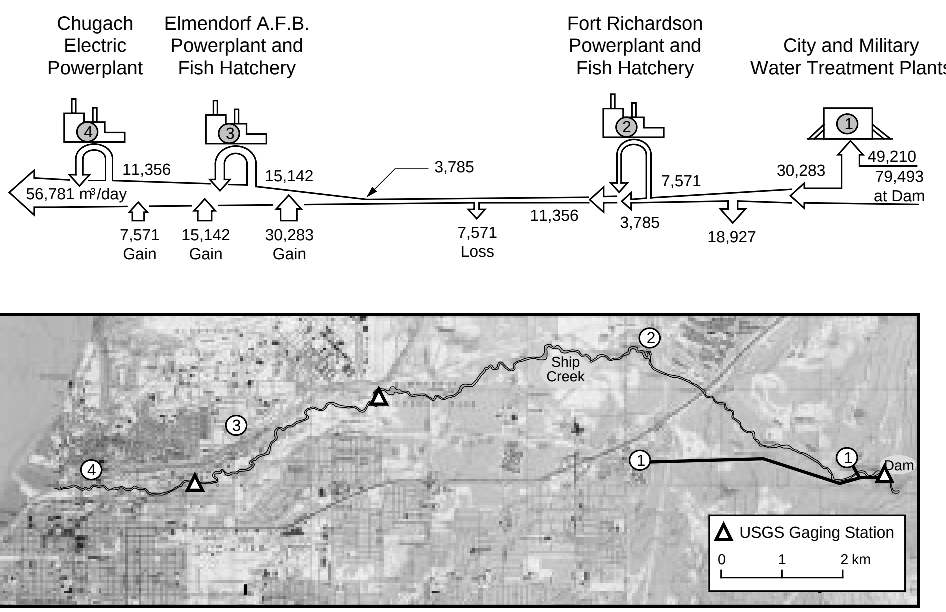



*Figure 25. Major water diversions along Ship Creek, showing shift from a losing channel on Fort Richardson to a gaining channel on Elmendorff Air Force Base. (After Barnwell et al. 1972.) 1–The combined capacity of the treatment plants is 64,352 m³/day. During the lowest flow days nearly every year, they cannot operate at full capacity. 2–Fort Richardson powerplant uses nearly all of the low flow in the stream for cooling and returns warm water to the channel. 3–Elmendorff Air Force Base's powerplant uses most of the low flow for cooling, then returns it to the channel. During the low flow months, the stream is supplemented with well water. 4–The Chugach Electric powerplant normally diverts about 11,500 m³/day for cooling water and returns it to the channel.*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An alternative model is supported by recent ground water data (USACE 1996b). Ground water flow below the southern portion of the cantonment area agrees with that of Freethy (1976), and the elevation of the potentiometric surface agrees with that of Cederstrom et al. (1964). However, ground water measurements below Ammunition Area A (AP-3471 and AP-3472) imply northwesterly flow here, with a limited amount of westerly divergence further to the south. These data would suggest that the confining layer projects beneath the Elmendorf Moraine. If this is true, then northwesterly flow of ground water could transfer contaminants from OU A and OU D underneath the Elmendorf Moraine and to the north and west.

The differences between these two models tell us that it is critical to determine whether or not the Elmendorf Moraine is a flow boundary. Both models are based on limited data that are mostly marginal to the cantonment. Freethy (1976) looked at the entire Anchorage Lowland, with Fort Richardson at the northern limit of his analysis. The USACE (1996b) had 13 wells to define the confining aquifer, but these were located mainly in the southern part of the cantonment. To resolve these questions, further studies are needed and additional measurements of ground water, including new wells, are required to improve our overall understanding of ground water flow below the Fort Richardson cantonment. The confining layer needs to be defined to determine if it is part of the Bootlegger Cove Formation, and therefore restricted by elevation (or paleobathymetry), or an extension of the Dishno Pond moraine. To evaluate potential contaminant transport pathways, it is critical to determine if the sand and gravel of the confined aquifer projects under the Elmendorf Moraine, thereby being a northwesterly path to Knik Arm. By addressing these questions, we will be better able to define the flow boundaries required before attempting a quantitative ground water flow model.

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## APPENDIX A: DESCRIPTION OF MAP UNITS

### Introduction

The material in this appendix is a draft report on the surficial geologic units of Fort Richardson prepared by H.R. Schmoll and L.A. Yehle of the U.S. Geological Survey. This section contains their most recent classification scheme and should be used when referring to the surficial geologic map (Plate 1).

The descriptions given here have been derived by combining the map unit descriptions of the five 1:25,000-scale surficial geologic quadrangle maps that were used in making the geologic map of Fort Richardson and vicinity (plate 1) and that have been published or are in preparation in the U.S. Geological Survey open-file report series. These maps are identified by number on Figure A1 and are listed below along with the quadrangle for which surficial geology is in preparation.

1. Anchorage B-7 NW
   (Yehle and Schmoll 1987b)
2. Anchorage B-8 SE / NE
   (Yehle et al. 1990)
3. Anchorage B-7 SW
   (Yehle and Schmoll 1989)
4. Anchorage A-8 NE
   (Schmoll et al. 1996)
5. Anchorage A-7 NW
   (Schmoll et al., in prep.)

The surficial geology of these quadrangles was mapped initially at scales of 1:63,360 (northern and eastern parts) and 1:24,000 (west–central and southwestern parts) by Schmoll and Dobrovolny mainly between 1965 and 1971 by interpretation of 1:40,0000-scale airphotos taken in 1957 and 1:20,000 scale airphotos taken in 1962. Field investigations were undertaken by Dobrovolny and Schmoll (1965–1971) and continued intermittently by Schmoll (1973–1983) and by Schmoll and Yehle (1984–1995). The original mapping was changed photographically to 1:25,000 scale by Yehle and Schmoll in 1986–1999 and, except in the southeastern part, the mountainous parts of the area were remapped by Yehle from 1:24,000-scale airphotos taken in 1972–1974. Additional detail in some other areas was derived by Schmoll and Yehle from these airphotos as well.

The geology of the lowland area was included in previous mapping at smaller scales by Dobrovolny and Miller (1950), Miller and Dobrovolny (1959), and Cederstrom et al. (1964), and at slightly larger scale but in a more generalized way that lacked traditional geologic map units by Schmoll and Dobrovolny (1972a). Other workers who reported on surficial geology of the area without providing detailed maps include Karlstrom

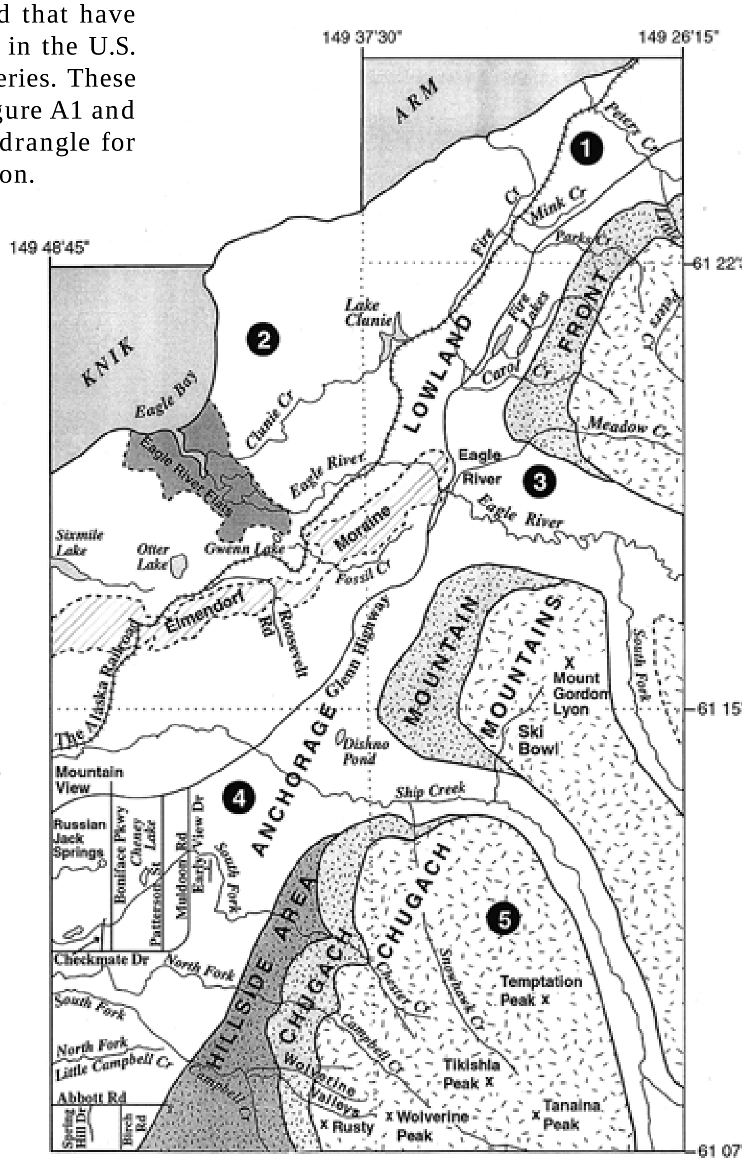


*Figure A1. Index map showing location of surficial geologic maps (circled numbers, listed in text) and selected geomorphic features.*

(1964, 1965), Reger and Updike (1983, 1989), and Schmoll et al. (in press). Bedrock crops out mainly in the Chugach Mountains, and was not examined in detail in any of the maps and reports cited above, but is mapped in parts of the area at 1:63,360 scale by Clark and Bartsch (1971). Bedrock of the entire area is included in the 1:250,000-scale reconnaissance map of Clark (1972) that served as the basis for subsequent regional compilations at the same scale by Magoon et al. (1976) and Winkler (1992).

The Fort Richardson map area lies athwart the boundary between two physiographic provinces, the Anchorage Lowland and the Chugach Mountains. This boundary extends diagonally across the map area from northeast to southwest and is marked by an abrupt rise of the mountains known as the Chugach Mountain Front. In the southern part of the map area, the margin of the lowland northwest of the front consists of a higher-lying, southwest-widening belt of foothills known as the Hillside area.

The characteristics of the surficial geologic materials delineated by the map units described here are based primarily on field observations; they are supported in part by laboratory analyses, especially of grain size, the descriptions of which follows the modified Wentworth grade scale (American Geological Institute 1989). Thickness estimates are based on unevenly distributed field observations and limited subsurface data; for many deposits, especially in the mountains, data are lacking and thickness estimates are based in large part on geomorphic considerations.

Especially near mapped bedrock or on mountain slopes mapped as colluvium, bedrock may be present at relatively shallow depth. Elsewhere, however, bedrock lies at considerable depth. In the descriptions that follow, “bedrock” refers to the metamorphic rocks of map unit *bo*. The term “older bedrock” is used only selectively to avoid ambiguity with the term “younger bedrock,” which is used for the Tertiary continental rocks of map unit *by*.

The units described here may be overlain by as much as 1 m of organic and windblown (including volcanic) materials that thicken locally and grade into map unit *p*. In the urbanized parts of the map area, much of this mantle has been removed or otherwise modified. Where the mapped deposit has also been significantly altered, in some places the landform destroyed, a suffix *u* is added to the map-unit designator. Slope information is derived from or based on geomorphic analogy to estimates presented in Schmoll and Dobrovolny (1972b), whose slope categories are used (Fig. A2). Stan-

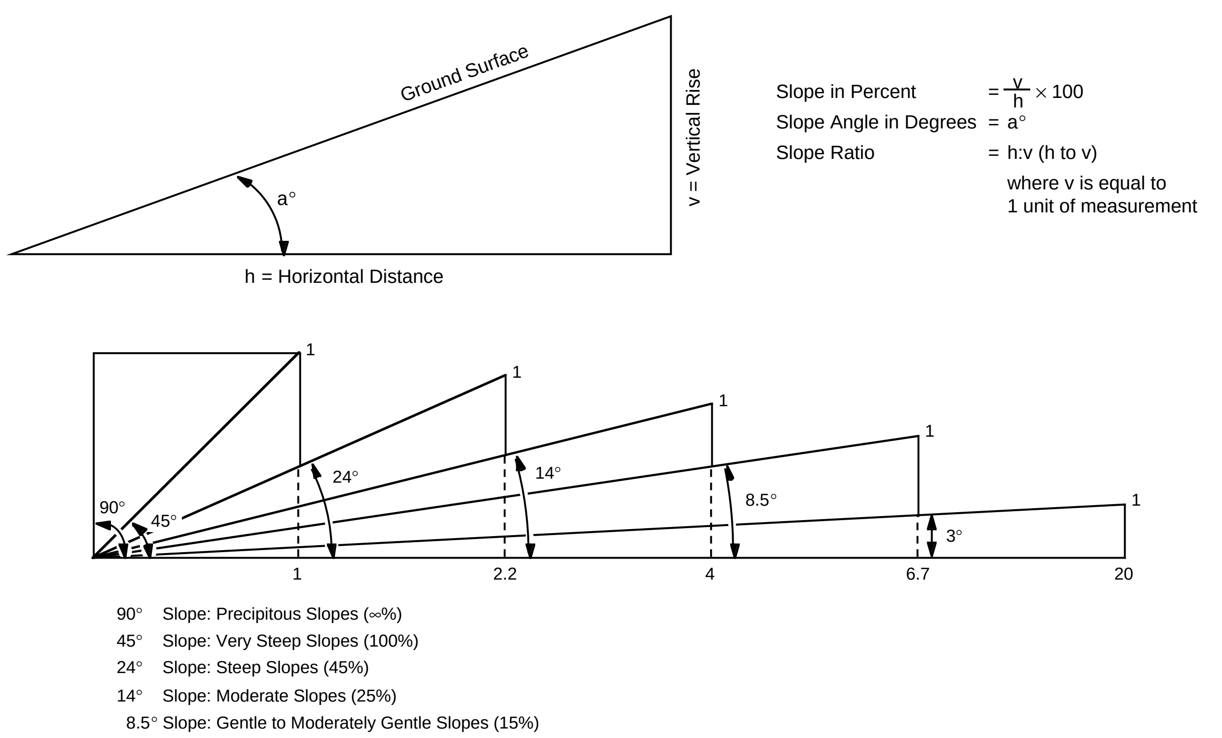


*Figure A2. Slope categories used in these descriptions. (After Schmoll and Dobrovolny 1972b.)*

dard age designations are omitted from map symbols because all units except bedrock are of Quaternary age. The correlation of map units is shown on Figure A3.

## Surficial deposits

Surficial deposits underlie the surface of the Anchorage Lowland and extend to depths of tens to at least 100 m (mainly west of the map area). They consist mostly of Pleistocene-age glacial drift that represents a sequence of several glaciations. Some of these deposits are found in stratigraphic sequences exposed in bluffs along Knik Arm and locally in exposures along streams and in roadcuts. Except for the uppermost one or two, most of the deposits in these sequences cannot be directly related to the deposits mapped at the surface. The deposits at the surface occur in well-defined landforms and include extensive areas of moraine and related glacioalluvial, glaciolacustrine, and glacio-

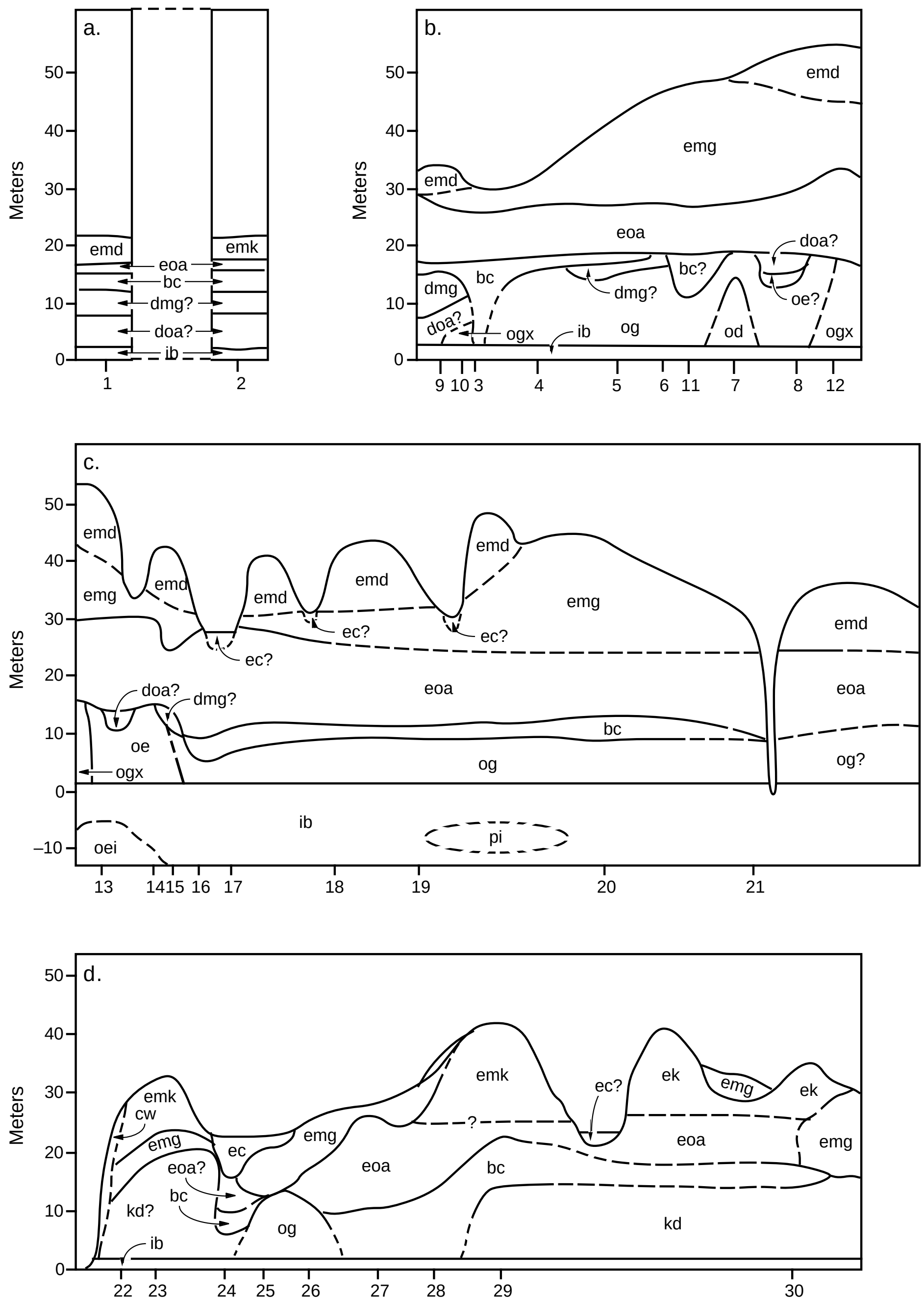


*Figure A3. Generalized stratigraphy exposed in bluffs along Knik Arm.*

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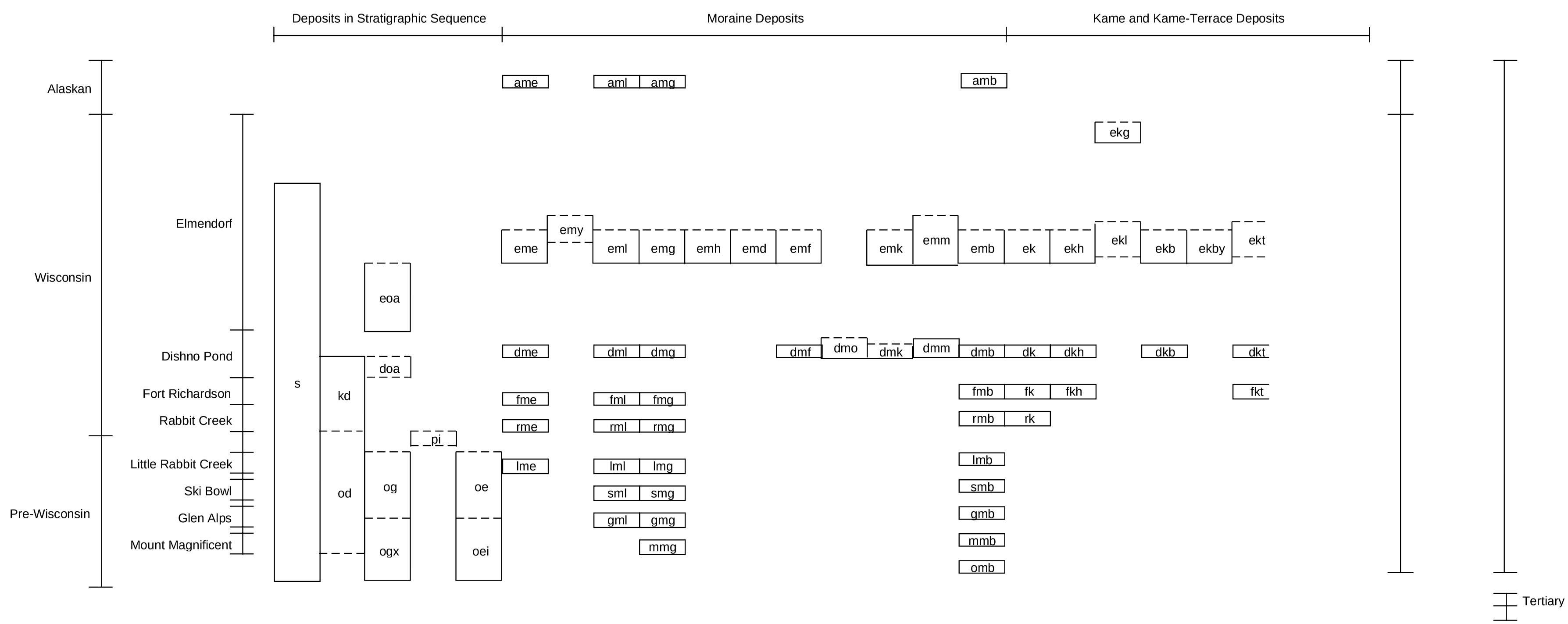


Figure A4. Correlation of map units



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estuarine deposits. Glacial deposits are common also within and on the walls of major mountain valleys, and quite prevalent, but thinner, along the Chugach Mountain Front; higher on the mountains, glacial deposits are more widely scattered. Colluvial deposits of Holocene and late Pleistocene age form an extensive veneer on especially the lower slopes of the Chugach Mountains. Other nonglacial deposits are more restricted in areal extent, although some are widely distributed. They include pond, peat, estuarine, alluvial, and anthropogenic deposits and are mostly Holocene in age.

*Deposits in stratigraphic sequence*

s **Deposits in stratigraphic sequence, undivided—**Deposits that crop out in bluffs along Knik Arm and are too narrow in map area to show individually; portrayed graphically in Figure A4. Individual units shown on that figure that are not otherwise shown on the map are described here, as are other deposits that occur only in stratigraphic sequence and that are shown on the map.

*Diamicton deposits.* These are poorly sorted mixtures of gravel, sand, silt, and minor clay-sized material that locally includes widely scattered boulders; they are commonly massive, with minor bedding locally. Mainly of glacial origin, they are equivalent to ground-moraine deposits.

kd **Knik diamicton (late Pleistocene)—**Includes interbeds of silt, sand, and gravel; crudely bedded in some places. Thickness at least 10 m. May be partly glacioestuarine in origin. Probably equivalent in age to Dishno Pond deposits, but may include older late Pleistocene deposits.

od **Older diamicton deposits (Pleistocene)—**Somewhat more oxidized and compact than most deposits of ground moraine at the surface. Thickness at least 10 m. Possibly equivalent in age to deposits older than those of the Rabbit Creek moraine.

*Glacioalluvial deposits.* These are chiefly pebble and cobble gravel with some interbedded sand; they are well bedded and sorted.

eoa **Advance outwash deposits related to Elmendorf Moraine (late Pleistocene)—**Thickness about 10 m. Deposited as the glacier advanced into glacioestuarine water or just prior to the time when the glacier terminus was farther to the northeast.

doa **Advance outwash deposits related to Dishno Pond moraines (late Pleistocene)—**Thickness 2 to 6 m, base of unit not exposed in places.

og
ogx **Older deposits (Pleistocene)—**Moderately oxidized to yellowish gray in most places. Thickness about 8 to 15 m; base of unit not exposed. Relationship to glacial deposits not evident. In places more strongly oxidized to yellowish-orange, possibly but not necessarily indicating deposits of substantially greater age.

oe **Older glacioestuarine deposits (late Pleistocene)—**Interbedded diamicton, variably pebbly to cobbly silty clay and clayey silt, silt, and fine to medium sand. Bedding commonly fairly even but strongly contorted locally. Thickness 10 to 14 m; base of unit not exposed. Probably deposited in glacioestuarine water that occupied ancestral Cook Inlet prior to glacier advances represented by Dishno Pond or earlier late Pleistocene moraines.

oei **Deposits that are somewhat indurated (Pleistocene)—**Well-bedded silt and clay locally and intermittently exposed below mean sea level. Bedding gently warped at one place.

pi **Interglacial pond deposits (Pleistocene)—**Chiefly silt and clay with some fine sand; commonly include marl and intermixed and interbedded organic material (peat, twigs, and wood, commonly compressed) whose age is beyond the range of the radiocarbon-dating method. As much as a few meters thick, overlain and underlain by glacial deposits. Exposed in a few roadcuts along Glenn Highway, at two places along Eagle River, and in one Knik Arm bluff.

*Moraine deposits*

These are subdivided primarily according to type of moraine (end, lateral, and several types of ground moraine) and subordinately according to correlations mainly with named end and lateral moraines that extend along the Chugach Mountain Front where their typical localities occur. Holocene-age moraines correlated generally with similarly situated moraines in the southeastern part of the Municipality of Anchorage, although not with the specifically named moraines there. The till that composes most moraine deposits is

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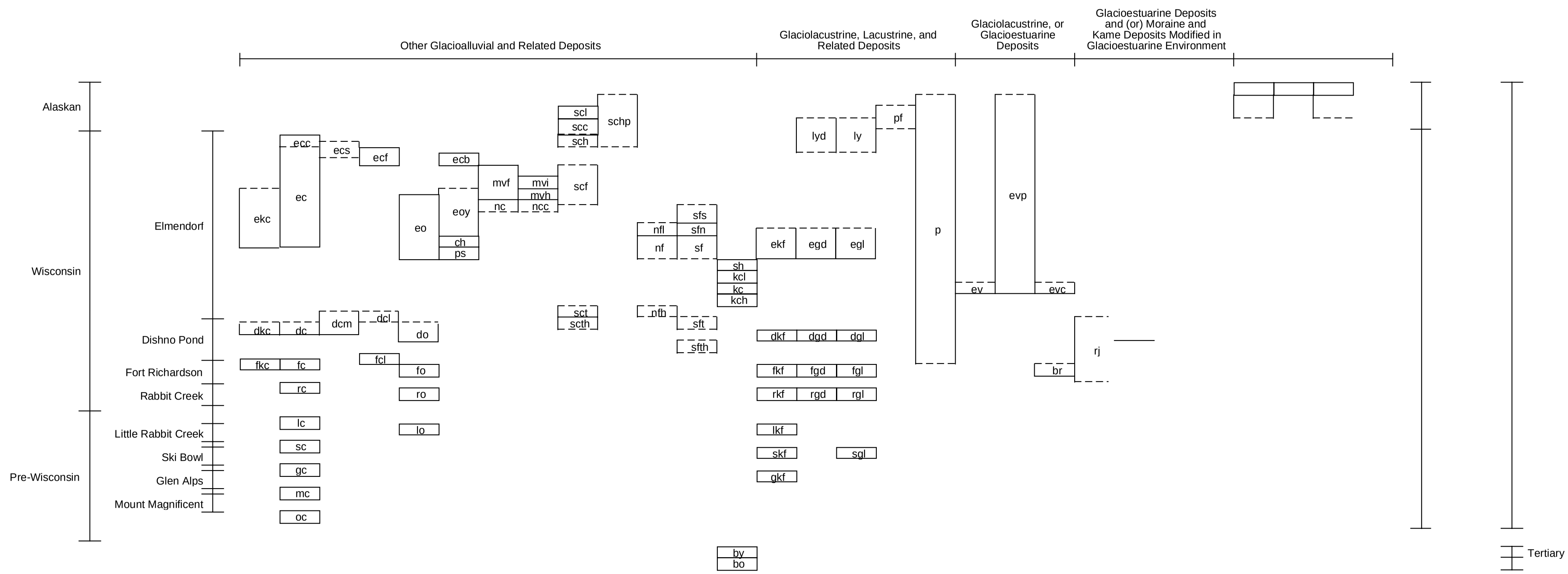


*Figure A4 (cont'd). Correlation of map units*



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chiefly a diamicton, consisting of massive, unsorted to poorly sorted mixtures of gravel, sand, silt, and relatively minor amounts of clay; in places it may consist of poorly sorted silty sandy gravel; it includes large boulders; locally it may include beds of gravel and sand. These deposits are generally moderately to well compacted.

*End-moraine deposits.* These are formed at the terminal areas of glaciers where the glacier front was relatively stationary. Contacts are well defined. Topography is irregularly hilly, in places being formed in well-defined gently arcing ridge complexes; slopes are gentle to moderate in small areas on some hill and ridge tops and in intervening swales, and are steep on hill and ridge sides. Except for the large Elmendorf Moraine in the Anchorage Lowland, deposits are restricted to small moraines in mountain valleys, most of which are correlated with varying degrees of certainty with named typical deposits in lateral moraines along the Chugach Mountain Front.

ame **Deposits of Alaskan moraines (Holocene)—** Mark terminal position of former small glaciers in heads of a few valleys tributary to Ship Creek in southeastern part of map area. Thickness probably 10 m or less.

eme
emeu **Deposits of main phase of Elmendorf Moraine (late Pleistocene)—**Mark limit of last significant readvance of large glacier in Knik Arm sector of Anchorage Lowland. Thickness probably 10 to 20 m in large Elmendorf Moraine complex (a formally named geographic feature) that also includes map units *emh* and *ekh*; may include gravel and sand near southern margin of complex. Probably less than 10 m thick in small moraines in largest Wolverine Valley and in upper part of Snowhawk Valley. *emeu* are deposits modified by urbanization or other anthropogenic activity.

emy **Deposits of younger phase of Elmendorf Moraine—**Occur in prominent ridge that marks a slight readvance of the glacier and that extends beyond the deposits of the main phase west of the map area.

dme
dmeu **Deposits of Dishno Pond moraines (late Pleistocene)—**Mark limits of readvances during general recession of glaciers from up-valley sources in mountain valleys. Thickness 10 m or more in Eagle River Valley and South Fork Valley, probably less than 10 m in Chester and Wolverine Valleys. *dmeu* are deposits modified by urbanization or other anthropogenic activity.

fme **Deposits of Fort Richardson moraines (late Pleistocene)—**Thickness may be as much as 10 m in remnant of major moraine in Ship Creek Valley in southeasternmost part of map area, less than 10 m in Chester and Wolverine Valleys, where mark minor termini of glaciers.

rme **Deposits of Rabbit Creek moraines (late Pleistocene)—**Thickness may be as much as 10 m in major moraine in Ship Creek Valley in southeasternmost part of map area, less than 10 m in valleys of Wolverine and South Fork Campbell Creeks where mark principal termini of glaciers.

lme **Deposits of Little Rabbit Creek moraines (Pleistocene)—**Probably more oxidized than younger end-moraine deposits. Thickness less than 1 m. Occur as remnants down-valley from better developed Rabbit Creek moraines in Wolverine Valleys.

*Lateral-moraine deposits.* These occur in narrow, well-defined ridges, as well as in less well-defined ridge segments, that mark side margins of former glaciers. Ridges descend gradually in altitude southwestward along the Chugach Mountain Front and are arranged en echelon; successively older groups of moraine ridges are generally better developed to the southwest. The approximate altitudinal ranges are given for each major lateral-moraine group; older moraine deposits are very poorly represented along the front by lateral moraines, if at all. These are locally present on the sides of several mountain valleys, descending down-valley. Contacts are generally well defined, except being gradational commonly with colluvium on the upslope sides and locally with other glacial deposits. Topography is moderately irregular; slopes are gentle to moderate on small areas on some ridge tops, and are steep on ridge sides, especially the downslope side. Bedrock may occur locally at shallow depths where a ridge is relatively high on the mountainside. These are more stable than other deposits on mountainsides, but some instability can be expected on steeper slopes.

aml **Deposits of Alaskan moraines (Holocene)—**Thickness probably less than 10 m. Single occurrence in head of valley tributary to Snowhawk Valley.

eml **Deposits of Elmendorf moraines (late Pleistocene)—**Thickness several to about

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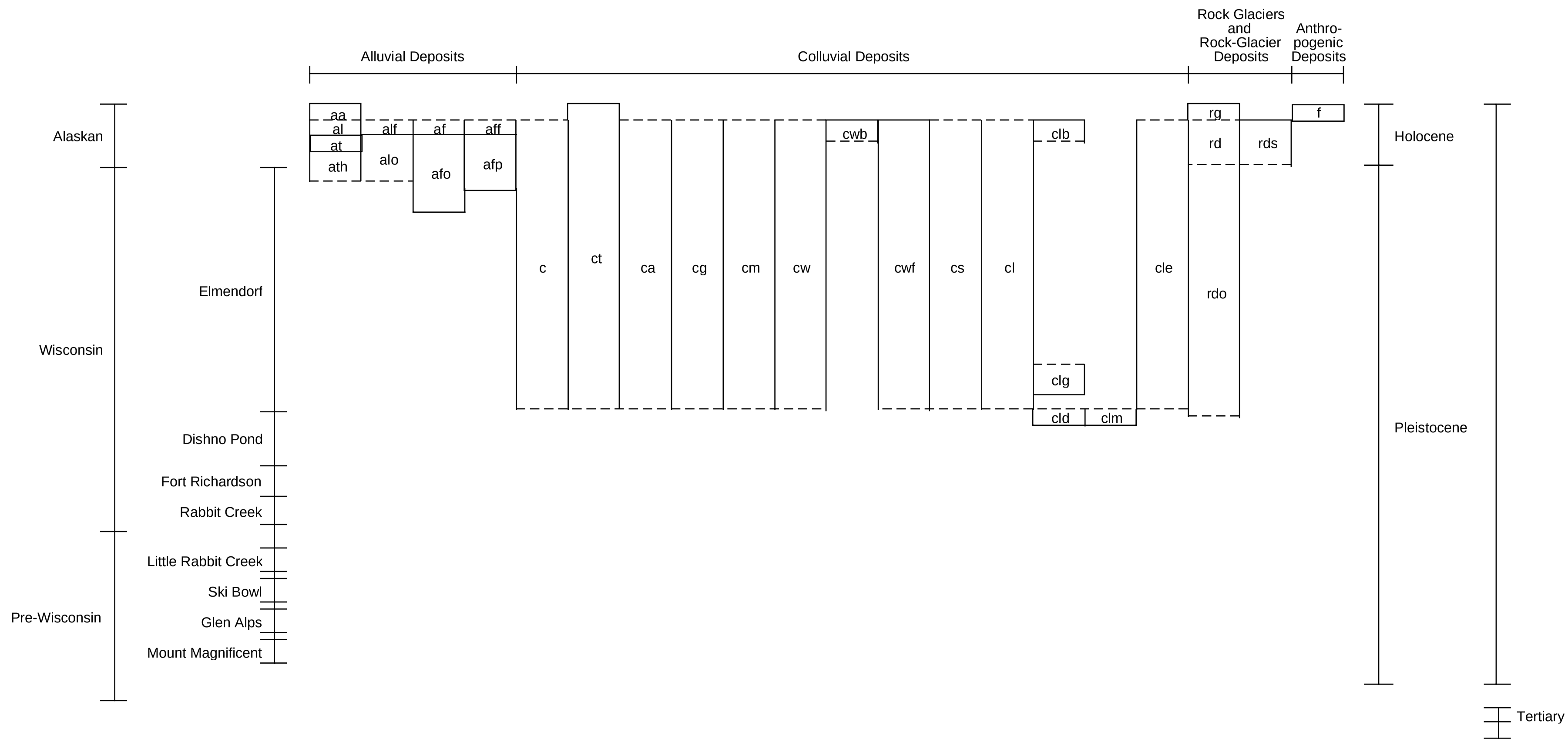


*Figure A4 (cont'd). Correlation of map units*

10 m. Occur discontinuously from Little Peters Creek (300 m) to Eagle River (260 m), where merge with end-moraine and kame deposits to form prominent Elmendorf Moraine complex; also present in valley tributary to Snowhawk Valley and in largest Wolverine Valley.

dml **Deposits of Dishno Pond moraines (late Pleistocene)—**Thickness probably 1 m to several meters, but as much as 15 m where better developed near Ship Creek. Extend discontinuously from Parks Creek (390 m) to south of Ship Creek (190 m); moderately well developed along Eagle River and its South Fork Valleys; single small occurrence in largest Wolverine Valley.

fml **Deposits of Fort Richardson moraines (late Pleistocene)—**Thickness probably several meters, except 10 to 15 m where better developed south of Chester Creek. Extend discontinuously from near Carol Creek (500 m); quite continuous southwest of Eagle River Valley, widening to form a well developed complex of ridges in the Hillside area (350 m). Also present extensively but discontinuously along sides of several mountain valleys.

rml **Deposits of Rabbit Creek moraines (late Pleistocene)—**Thickness ranges from several meters in the northeastern to at least 10 m in the southwestern ends of the distribution. Discontinuous from near Carol Creek (580 m) to South Fork Campbell Creek, where well developed (440 m).

lml **Deposits of Little Rabbit Creek moraines (Pleistocene)—**May be more oxidized than younger lateral-moraine deposits. Thickness probably a few to several meters. Extend quite discontinuously southwestward from near South Fork Campbell Creek (500 m); occur also at one locality in Chester Creek Valley.

sml **Deposits of Ski Bowl moraines (Pleistocene)—**Probably more compacted and oxidized than younger lateral-moraine deposits. Thickness probably several meters. Contacts more gradational and topography more subdued than those of younger deposits. Occur along Chugach Mountain Front in small saddle between front and Ship Creek Valley (typical area) and as scattered remnants farther up Ship Creek Valley and in Snowhawk Valley.

gml **Deposits of Glen Alps moraines (Pleistocene)—**Probably well compacted and oxidized. Thickness poorly known, probably a few to several meters. Contacts gradational. Topography includes remnant ridges and patches of hummocky ground; slopes moderate to steep. Occur high on slopes of North Fork Campbell Creek Valley and in mountain pass north of Ship Creek.

*Ground-moraine deposits*. These are formed mostly beneath glaciers; they are generally thinner and found in landforms commonly more subdued than the well-developed ridges and hills of end- and lateral-moraine deposits. Where ground-moraine deposits are extensively developed, those in several distinctive types of landform are mapped separately. They occur in the Anchorage Lowland mainly north of the Elmendorf Moraine; south of it most ground-moraine deposits are concealed by younger deposits or modified by the action of glacioestuarine water, or both. Occurrences along the Chugach Mountain Front and within mountain valleys are more widely scattered and restricted in area.

amg **Deposits of Alaskan moraines (Holocene)—**Thickness poorly known, probably several meters. Occur only in a few mountain valley heads in southeastern part of map area.

amb **Deposits that thinly mantle bedrock—**Similar to other ground-moraine deposits but may be only a few meters thick. Bedrock may be present at surface locally. Single occurrence in valley head tributary to Snowhawk Valley.

emg **Deposits of the Elmendorf Moraine (late**
emgu **Pleistocene)—**Thickness several to about 12 m, except only a few meters in mountain valleys. May include older ground-moraine deposits at depth. Contacts generally well defined but may be gradational with other ground-moraine deposits. Topography generally smooth to very gently hummocky, slopes gentle to moderately gentle. Widespread north of the Elmendorf (end) Moraine complex. Single occurrences in largest Wolverine Valley and in valley tributary to Snowhawk Valley. *emgu* are deposits modified by urbanization.

emh **Deposits with high relief—**Thickness
emhu may be greater than in other ground-moraine deposits, perhaps 15 to 20 m. Topography more boldly hummocky to hilly

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and slopes steeper. Occur in association with end-moraine deposits as part of Elmendorf Moraine complex, but not formed in the well-developed ridges characteristic of those deposits. *emhu*, deposits modified by urbanization or other anthropogenic activity.

emd **Deposits in well-developed drumlins—** Thickness may be as much as 15 to 20 m. Occur in elongate hills with moderately steep side slopes that merge laterally into low-relief terrain of other deposits, commonly other ground moraine. Best developed northeast and southwest of Eagle River Flats.

emf **Deposits in fluted terrain—**Similar to other ground-moraine deposits but formed in hills more elongate and of lower relief than drumlins with which they are associated. Limited to a few occurrences near Lake Clunie.

emk
emku **Deposits that include some kame deposits—**May include gravel and sand either in extensive areas that are not readily distinguishable from ground moraine or locally in areas too small to map separately. Occur mainly north and south of Peters Creek in association with kame fields and at a few localities farther southwest. *emku* are deposits modified by urbanization or other anthropogenic activity.

emm **Deposits modified by glacial lake water—** Similar to other ground-moraine deposits but surface of deposits appears to have been winnowed and include better-sorted silt, sand, and gravel. Single occurrence along Eagle River about 3 km east of Glenn Highway.

emb **Deposits that thinly mantle bedrock—**Similar to other ground-moraine deposits but may be only a few meters thick. Bedrock may be present at ground surface locally. Occur locally along lower part of and adjacent to Chugach Mountain Front and at one place in valley tributary to Snowhawk Valley.

dmg
dmgu **Deposits of Dishno Pond moraines (late Pleistocene)—**Thickness probably several to 10 m. Contacts generally well defined, may be gradational with colluvium. Topography smooth to gently hummocky, slopes gentle to moderate. Occur mainly near Dishno Pond (typical area), in Eagle River Valley, and northward along the Chugach Mountain Front. *dmgu* are deposits modified by urbanization or other anthropogenic activity.

dmf **Deposits in fluted terrain—**Similar to other ground-moraine deposits but occur in well-developed, long, relatively narrow ridges several meters high, parallel to direction of ice flow, and separated by channel-like depressions. Occur only in Eagle River Valley just east of Eagle River community.

dmo **Deposits overridden by later (Elmendorf) glacier ice—**Probably similar to fluted ground-moraine deposits but occur in very subdued ridges. Present only down-valley from fluted terrain.

dmk **Deposits that include some kame deposits—** More likely to include gravel and sand than other ground-moraine deposits. Restricted to a few localities near Dishno Pond.

dmm **Deposits modified by glacial lake water—** Thickness possibly a few meters in an irregularly thick mantle of somewhat better sorted, more gravelly diamicton that forms a lag accumulation seemingly originated by the winnowing action of glacial lake water. Probably gradational at depth mostly to unmodified glacial diamicton. Occur at a few places in Eagle River Valley along north side of river opposite mouth of South Fork Valley.

dmb **Deposits that thinly mantle bedrock—**Similar to other ground-moraine deposits but only a few meters thick. Bedrock may be present locally at ground surface. Single occurrence near mouth of South Fork Valley.

fmg **Deposits of Fort Richardson moraines (late Pleistocene)—**Thickness probably a few to several meters. Contacts well defined except gradational with bedrock and lateral-moraine and colluvial deposits. Topography generally smooth, slopes moderate. Occur mainly in South Fork (Eagle River) Valley and locally downslope from lateral moraines along Chugach Mountain Front; occur also in Wolverine Valleys in southern part of map area.

fmb **Deposits that thinly mantle bedrock—** Thickness probably a few meters or less. Bedrock outcrops present locally; may include some admixed rubble. Occur at a few scattered localities along Chugach Mountain Front and in upper part of North Fork Campbell Creek Valley.

rmg **Deposits of Rabbit Creek moraines (late**

**Pleistocene)—**Thickness probably a few meters. Contacts gradational with lateral-moraine and colluvial deposits. Topography smooth, slopes gentle to moderate. Occur extensively in valleys of Chester Creek and the north and south forks of Campbell Creek, and at widely scattered localities along the Chugach Mountain Front.

rmb **Deposits that thinly mantle bedrock—**Thickness about 1 m to a few meters. Bedrock outcrops commonly present; include admixed rubble. Contacts well defined except gradational with bedrock. Topography smooth, slopes gentle. A few occurrences along Chugach Mountain Front.

lmg **Deposits of Little Rabbit Creek moraines (Pleistocene)—**May be more oxidized than younger deposits. Thickness probably only a few meters. Contacts gradational. Topography smooth, slopes gentle to moderate. Occur in Ship Creek Valley and in a few places along Chugach Mountain Front south of North Fork Campbell Creek.

lmb **Deposits that thinly mantle bedrock—**Thickness may be about 1 m. Some bedrock outcrops present; include admixed rubble. Occur at several places along Chugach Mountain Front southward from the north side of Ship Creek.

smg **Deposits of Ski Bowl moraines (Pleistocene)—**Probably more oxidized than younger deposits. Thickness a few to several meters. Contacts gradational. Topography smooth, slopes moderate. Occur in broad areas where mountain valleys emerge along the Chugach Mountain Front, at scattered localities on mountain ridges (especially south of Meadow Creek), and at one locality in Ship Creek Valley.

smb **Deposits that thinly mantle bedrock—**Thickness possibly 1 m to a few meters. Small bedrock outcrops common; admixed with or containing mostly rubble, especially in small map-unit areas. Topography smooth, slopes gentle to moderate. Occur at scattered localities along Eagle River Valley and south of there near the northwestern ends of mountain interfluve ridges, especially where Ship Creek Valley emerges at the Chugach Mountain Front.

gmg **Deposits of Glen Alps moraines (Pleistocene)—**Probably more oxidized than younger deposits. Thickness probably a few meters. Contacts gradational. Topography smooth, slopes gentle to moderate, locally steeper. Occur in Chester Creek Valley.

gmb **Deposits that thinly mantle bedrock—**The more common mode of occurrence for Glen Alps deposits. Thickness quite variable, probably a few meters or less. Bedrock outcrops common; admixed with or consisting mostly of rubble. Topography somewhat more irregular than in areas of other ground moraine, slopes locally steep. Occur high on slopes of Ship Creek Valley and on mountain interfluve ridge between North and South Forks of Campbell Creek.

mmg **Deposits of Mount Magnificent moraines (Pleistocene)—**Probably more oxidized and compacted than older deposits; clayey matrix common locally. Thickness commonly a few meters, perhaps thicker where more extensive. Contacts fairly well defined to gradational. Topography smooth to slightly irregular, slopes mainly gentle. Occur on high-level glacially planed bedrock surfaces between Little Peters and Meadow Creeks (typical area) and at a few smaller localities on interfluve ridges adjacent to Ship Creek and North Fork Campbell Creek Valleys.

mmb **Deposits that include mainly bedrock rubble—**Thickness probably 1 m or little more; in many places may consist only of widely scattered erratics; bedrock outcrops common. Contacts gradational. Topography fairly smooth, slopes gentle, somewhat steeper near contacts. Occur at scattered localities high on mountain ridges near Carol, Ship, and North Fork Campbell Creeks.

omb **Older deposits that include mainly bedrock rubble (Pleistocene)—**Thickness less than 1 m; in many places consist of rubble with widely scattered erratics; bedrock outcrops common. Contacts fairly well defined. Topography smooth, slopes gentle to nearly flat. Occur high on interfluve ridges near South Fork Eagle River Valley and Snowhawk Valley, near McHugh Peak, and on summit of Flattop Mountain. Altitudinally similar to deposits on summit of Mount Susitna (west side of Cook Inlet Basin).

*Kame and kame-terrace deposits*

Kame deposits and kame-terrace deposits are

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both glacioalluvial in origin and closely associated with glacier ice. Kame deposits are formed by running water within a glacier during the early stages of stagnation when large amounts of glacier ice were still present. They occur in fields of locally prominent landforms that include irregular hills and areas of sharply hummocky terrain. Kame fields are especially well developed in the margins of the Anchorage Lowland down-valley from major mountain valleys, where copious quantities of water drained from the valleys into the glacier. Some kames of especially high relief are mapped separately, but the significance of differences in relief is not evident. Eskers (similarly formed deposits in long, commonly sinuous ridges) of substantial size have not been recognized, but several small esker-like ridges are included in kame deposits. Kame-terrace deposits were formed by running water outside the margin of a glacier and occur in long, narrow landforms that have smoothly sloping surfaces with prominent scarps on their ice-proximal (downslope) sides that developed when the adjacent glacier melted.

*Kame deposits (late Pleistocene)*. These are chiefly pebble and cobble gravel and sand, moderately to well bedded, in places chaotically; they are generally well sorted; they include some silt, and, especially in the cores of hills, diamicton; locally, they may include large boulders. They are moderately loose, but compact in the cores of some hills. Contacts are generally well defined, merging with end- and lateral-moraine deposits. Topography is sharply hilly to hummocky, with some local depressions; slopes are moderate to steep, except being gentle to nearly flat in minor channels, on depression floors, and on some hilltops.

ek, eku — **Deposits of the Elmendorf Moraine—**In landforms of moderate to low relief. Thickness several to a few tens of meters. Widely distributed within areas of ground moraine. *eku* are deposits modified by urbanization.

ekh, ekhu — **Deposits that exhibit high relief—**In landforms of broader shape than most kames, and locally with steeper side slopes. Thickness possibly several tens of meters; locally may include larger cores of diamicton than smaller kames. Associated mainly with end-moraine deposits. *ekhu* are deposits modified by urbanization.

ekg — **Deposits near Gwenn Lake—**In landforms of fairly high relief. Thickness possibly a few tens of meters. Formed by ancestral Eagle River as part of a glacioalluvial train that extended from glacial Lake Eagle (in Eagle River Valley), through Fossil Creek channel, and into the Otter-Sixmile channel; in this sector the stream entered the margin of the glacier and deposits were emplaced beneath it.

ekl — **Deposits of low relief—**Occur in fairly broad areas with moderately irregular topography that lie at intermediate levels between higher-lying kames and channels cut below them; may be pitted outwash deposits. Thickness perhaps only a few meters. Occur mainly southwest, locally northeast, of Peters Creek Valley in areas of kames and ground moraine. May grade to some deposits mapped farther southwest as kame-channel deposits.

ekb — **Deposits that thinly mantle older bedrock—**Similar to other kame deposits but may be only a few meters thick; bedrock may be exposed locally. Occur only near Upper and Lower Fire Lakes.

ekby — **Deposits that thinly mantle younger bedrock—**Similar to other kame deposits but may be only 1 m to a few meters thick; bedrock exposed locally; some apparent bedrock that includes thin coal beds instead may be detached blocks of rock that were shoved by glacier ice. Occur only near and north of Eagle River community.

dk, dku — **Deposits of Dishno Pond moraines—**In landforms of moderately high relief. Thickness several to a few tens of meters. Occur principally in prominent kame field south of Ship Creek, locally farther northeast. *dku* are deposits modified by urbanization or other anthropogenic activity.

dkh — **Deposits that exhibit high relief—**Probably thicker than other kame deposits, and topography more bold. Occur mainly in kame field south of Ship Creek; single occurrence east of Eagle River community.

dkb — **Deposits that thinly mantle older bedrock—**Thickness may be only a few meters; bedrock may be exposed locally. A few occurrences along base of Chugach Mountain Front southwest of Eagle River.

fk, fku — **Deposits of Fort Richardson moraines—**Thickness probably a few to a few tens of meters. Occur mainly in a prominent kame field that dominates the Hillside area

downslope from lateral moraines and that extends southwestward along the Chugach Mountain Front from north of Chester Creek. *fku* are deposits modified by urbanization.

fkh **Deposits that exhibit high relief—**Probably thicker than other kame deposits. Contacts gradational with them. Occur locally within prominent kame field in Hillside area, mainly south of North Fork Campbell Creek.

rk **Deposits of Rabbit Creek moraines—**Thickness probably several meters. Occur near Carol Creek.

*Kame-terrace deposits (late Pleistocene).* These are chiefly pebble and cobble gravel and sand, moderately to well bedded and sorted; locally, they may include boulders. They are moderately loose, with contacts being generally well defined. Topography is smooth, with slopes being gentle except in the steep scarp at the edges of the terraces.

ekt **Deposits of the Elmendorf Moraine—**Thickness may be a few to as much as several tens of meters. Occur near Little Peters Creek where the valley intersects the Chugach Mountain Front.

ektr, ektru **Roosevelt Road deposits—**Younger deposits that occur in three levels as part of glacioalluvial train formed when ancestral Eagle River extended from glacial Lake Eagle (in Eagle River Valley), through Fossil Creek channel, and into Otter-Sixmile channel. Equivalent to deposits in some terrace levels in Fossil Creek channel; highest level deposits possibly equivalent to low-level Tuomi Lake deposits. *ektru* are deposits modified by urbanization or other anthropogenic activity.

ektt **Tuomi Lake deposits—**Occur in two levels that were part of same glacioalluvial train as Roosevelt Road deposits. Occur only south of Sixmile Lake.

dkt, dktu **Deposits of Dishno Pond moraines—**Thickness probably a few to several meters. Occur in two levels north of Ship Creek. *dktu* are deposits modified by urbanization.

fkt **Deposits of Fort Richardson moraines—**Thickness probably a few to several meters. Occur in Hillside area in a single dissected terrace near North Fork Campbell Creek.

*Other glacioalluvial and related alluvial deposits*

These are dominantly gravel and sand, subdivided into 1) kame-channel, 2) meltwater-channel, 3) outwash-train, and 4) alluvial deposits. The first three categories constitute glacioalluvial deposits that formed in areas outside of glaciers or recently abandoned by them. Alluvial deposits formed farther away from glaciers and after they had a direct influence on deposition. Streams in which they formed commonly led to deltas west of the map area that were marginal to ancestral Cook Inlet. These deposits are listed together because they follow one another sequentially or grade from one to another to form nearly a continuum both in space and time. The glacioalluvial deposits are named from the associated glacial deposits, whereas the alluvial deposits are named separately.

*Kame-channel deposits (late Pleistocene).* These are chiefly pebble and cobble gravel and sand. Locally, they may include some finer materials, and may include pitted outwash or meltwater-channel deposits, or both. Thickness is probably at least a few meters. Contacts are well defined. Topography is slightly hummocky in broad, channel-like landforms of generally low relief that commonly lie at levels intermediate between kame and ground-moraine deposits of higher relief and lower-lying meltwater channels with gently sloping smooth surfaces; slopes are typically gentle but locally are steeper where hummocks are well developed.

ekc **Deposits of the Elmendorf Moraine—**Occur extensively northeast of the Eagle River Flats. May grade into deposits mapped as *ekl* farther northeast.

dkc **Deposits of Dishno Pond moraines—**Occur locally in kame field southwest of Ship Creek.

fkc **Deposits of Fort Richardson moraines—**A few occurrences in the Hillside area near South Fork Campbell Creek.

*Meltwater-channel deposits.* These are chiefly gravel and sand, well bedded and sorted; at the surface they may include some finer-grained material with thin organic accumulations. Thickness is probably 1 m to a few meters except as noted. In places, channel deposits may be very thin or absent and ground-moraine deposits or bedrock may lie at shallow depth or floor the channel. Peat deposits may be present locally, especially in smaller channels. Contacts are well

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defined. Topography is smooth and slopes are gentle.

ec **Deposits of the Elmendorf Moraine (late Pleistocene)—**Occur in narrow channels along the Chugach Mountain Front and in broader channels commonly well incised below the level of ground moraine on the Anchorage Lowland. Generally older than deposits mapped separately in the following units, but in northern part of map area includes some younger deposits as well.

ecc eccu **Clunie Creek glacioalluvial deposits—**Thickness may be a few tens of meters, more commonly about 10 m; probably thinner in narrower channels. Occur mainly in major channels cut well below, and thus younger than, channel deposits mapped as *ec*; best developed near Lake Clunie and in the valley of Clunie Creek, the typical locality, where deposits occur at three levels. May grade northeast, however, into channel deposits mapped as *ec*. Formed when the glacier had retreated substantially northeast. *eccu* are deposits modified by urbanization.

ecs **Sixmile Lake alluvial deposits—**Occur in three levels near Sixmile Lake, the typical locality. Formed when ancestral Eagle River last occupied the Otter-Sixmile channel; may be equivalent in part to youngest Fossil Creek or oldest Clunie Creek deposits.

ecf ecfu **Fossil Creek glacioalluvial deposits—**Occur in a series of well-formed terrace levels within the prominent, single channel of Fossil Creek (the typical locality) that is cut as much as 50 m lower than the surface of the Elmendorf Moraine as well as the adjacent Mountain View alluvial fan. Graded to various levels of Gwenn Lake kame and Roosevelt Road kame-terrace deposits; formed when ancestral Eagle River was first able to cut through the Elmendorf Moraine rather than having to flow more southwestwardly around it. *ecfu* are deposits modified by urbanization.

dc dcu **Deposits of Dishno Pond moraines (late Pleistocene)—**Occur in narrow channels extending along the Chugach Mountain Front from the vicinity of Meadow Creek in the northeast and descending southwestward to near Chester Creek on the Anchorage Lowland; occur locally on the flanks of Eagle River Valley. *dcu* are deposits modified by urbanization.

dcm **Deposits overridden by glacier ice—**May be relatively thin or include mainly diamicton, or both. Merge laterally with moraine deposits that have been overridden by glacier ice (map unit *dmo*) Occur only east of Eagle River community.

dcl **Lower-level deposits—**Occur in a few places near Chester Creek and along Glenn Highway north of Ship Creek; farther northeast not differentiated from map unit *dc*.

fc **Deposits of Fort Richardson moraines (late Pleistocene)—**Occur in numerous narrow channels mainly extending from near Carol Creek southwestward along Chugach Mountain Front into Hillside area; found locally in a valley tributary to South Fork Campbell Creek.

fcl **Lower-level deposits—**Occur mainly between Chester Creek and South Fork Campbell Creek at altitudes substantially lower than those of other channel deposits; may grade to Klatt Road deposits.

rc **Deposits of Rabbit Creek moraines (late Pleistocene)—**Occur mainly in relatively short, narrow channels near the upper boundary of the Hillside area south of South Fork Campbell Creek; found also along the Chugach Mountain Front in widely scattered localities from Carol Creek to south of Ship Creek.

lc **Deposits of Little Rabbit Creek moraines (Pleistocene)—**May be somewhat more oxidized than younger channel deposits. Occur in isolated localities along Chugach Mountain Front near Ship Creek Valley and south of Chester Creek.

sc **Deposits of Ski Bowl moraines (Pleistocene)—**Probably more oxidized than younger channel deposits. Occur in several isolated places on mountain interfluve ridges.

gc **Deposits of Glen Alps moraines (Pleistocene)—**Probably more oxidized than younger channel deposits. Occur at a few localities high on mountain interfluve ridges north of Chester Creek Valley and near North Fork Campbell Creek Valley.

mc **Deposits of Mount Magnificent moraines (Pleistocene)—**More oxidized than younger channel deposits. May include much bedrock rubble. Occur in the typical area

north of Meadow Creek and on a few prominent topographic saddles high on mountain interfluve ridges in southern part of map area.

oc **Older deposits (Pleistocene)—**Gravel and sand of these deposits may be less well sorted, thinner, and probably more oxidized than other channel deposits; may include much bedrock rubble and small bedrock outcrops. Tentatively identified at a few places on high ridges near Mount Gordon Lyon and near benchmark Rusty.

*Outwash-train deposits.* These are chiefly pebble and cobble gravel and sand, well bedded and well sorted, that accumulated mainly out in front of the Elmendorf Moraine and downstream from valley glaciers in mountain valleys. They are now found mainly in terraces and channels. Contacts are well defined. Topography is smooth and slopes are gentle, except where they become steep at terrace edges.

eo
eou **Deposits related to Elmendorf moraines (late Pleistocene)—**Thickness several to a few tens of meters in fan-like remnants that extend south from front of the Elmendorf Moraine complex and that probably were once more extensive. Some deposits appear to emerge from within moraine complex, probably reflecting fluctuations of the glacier front. Small occurrences in largest Wolverine and Chester Creek Valleys likely to be only a few meters thick. *eou* are deposits modified by urbanization or other anthropogenic activity.

ch
chu **Cheney Lake deposits—**Thickness at least 10 m. Occur as remnants in channel now occupied by Cheney Lake, where principal deposit largely removed by excavation, and as a few terrace remnants nearby. Possibly an extension of outwash from Elmendorf Moraine (map unit *eo*). *chu* are deposits modified by urbanization.

ps
psu **Patterson Street deposits—**Thickness may be as much as 10 m. Occur in channel remnants that extend discontinuously from Glenn Highway south of Ship Creek to North Fork Campbell Creek. Probably outwash from Elmendorf Moraine (discontinuously traceable to map unit *eo*). *psu* are deposits modified by urbanization.

eoy
eoyu **Deposits of the younger phase of the Elmendorf Moraine—**Probably thinner than main-phase deposits and at lower level. Possibly coeval with Mountain View alluvial-fan deposits with which they appear to merge. Occur only near west edge of map area. *eoyu* are deposits modified by urbanization or other anthropogenic activity.

ecb **Bluff Road deposits—**Thickness probably only a few meters, but underlain by Mountain View deposits from which they may not be distinguished readily. Occur as filling of shallow channel that emanated from younger phase of the Elmendorf Moraine and that was incised across Mountain View alluvial-fan deposits. Underlie part of runways and housing area on Elmendorf Air Force Base.

do **Deposits related to Dishno Pond moraines (late Pleistocene)—**Thickness probably a few meters. Occur in low terraces in Ship Creek and Chester Creek Valleys.

fo **Deposits related to Fort Richardson moraines (late Pleistocene)—**Thickness at least a few meters in Ship Creek and Snowhawk Valleys where they form major terrace and may grade to (but are no longer in contact with) glacial lake delta deposits, map unit *fgd*. Probably thinner in Chester Creek Valley and other small valleys to the south.

ro **Deposits related to Rabbit Creek moraines (late Pleistocene)—**Thickness probably a few to several meters in Ship Creek Valley adjacent to major end moraines; probably thinner in Wolverine Valleys.

lo **Deposits related to Little Rabbit Creek moraines (Pleistocene)—**May be somewhat more oxidized than younger outwash-train deposits. Thickness probably 1 m to a few meters. Mapped at two places in largest Wolverine Valley; in smaller Wolverine Valleys included with kame-fan deposits into which they grade, map unit *lkf*.

*Alluvial deposits of Eagle River source (late Pleistocene).* These are dominantly gravel and sand, well bedded and well sorted, that occur at several levels but are found mainly in a major channel and a large alluvial fan. They formed when water of glacial Lake Eagle (in Eagle River Valley), dammed by the Elmendorf glacier, broke out and flowed southwestward around the ice as an ancestral Eagle River, truncating outwash deposits that emanated directly from the glacier. Such a

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breakout process probably occurred repeatedly, resulting in a complex of deposits. Although commonly referred to as "Naptowne outwash," these deposits are not outwash in the strict sense. Contacts are well defined. Topography is smooth, with slopes being gentle to very gentle.

mvf
mvfu **Mountain View alluvial-fan deposits—** Chiefly cobble gravel near apex of fan; grade southwestward to finer grained gravel and sand; mainly sand at distal end west of map area. Thickness 10 m or more. Occur in broad, low-gradient alluvial fan that heads at south edge of the broad Eagle River Valley where it emerges from the Chugach Mountains and that extends southwestward to downtown Anchorage. Named from community of Mountain View at west edge of map area. Complex nature of fan indicated by presence of several levels near head of fan separated by small scarps, although these levels have not been correlated directly with two higher-level remnants mapped farther down the fan, mainly south of Ship Creek. In that vicinity the fan has been dissected by ancestral Ship Creek and subsequent deposition has partly filled some of the resulting channels. *mvfu* are deposits modified by urbanization or other anthropogenic activity.

mvi **Deposits at intermediate level—**Occur in a remnant slightly higher than main part of fan; extend southwestward from south of Ship Creek to south of Glenn Highway.

mvh
mvhu **Deposits at highest level—**Occur in remnants substantially higher than main fan; extend discontinuously from north of Ship Creek to Middle Fork Chester Creek. *mvhu* are deposits modified by urbanization.

nc
ncu **Nunaka Valley channel deposits—**Thickness at least 10 m. Occupy major channel that lies at higher altitude than, and to the southeast of, Mountain View fan. Extend from Ship Creek to South Fork Chester Creek. Probably represent earlier episode of drainage from glacial Lake Eagle; alternatively, could be derived largely from Ship Creek. *ncu* are deposits modified by urbanization.

ncc
nccu **Checkmate boulder-rich deposits—**Occur in smaller channel that branches off major channel and lies southeast of it and that is now occupied by underfit South Fork Chester Creek. Erosion in this channel was less deep than in major channel and was not followed by significant deposition of gravel and sand. Instead, deposits are finer-grained or more poorly sorted and numerous boulders are present on ground surface. May represent lag concentrate from erosion of earlier glacioestuarine or moraine deposits, or both, or may have formed as debris flow developed during rapid erosion of those deposits. Peat deposits may have accumulated at surface in places, but most of these have been removed during urbanization. *nccu* are deposits further modified by urbanization.

*Alluvial deposits of local mountain-valley source.* These are chiefly gravel and sand, well bedded and well sorted. Contacts are well defined except as noted. They occur mainly in large alluvial fans, in terrace remnants at higher levels, and in channels that are cut below the level of fans or extend from them. They formed both before and after the incursion of the Eagle River; some high-level deposits probably correlate with outwash from Elmendorf glacier.

The **Ship Creek deposits** are subdivided into deposits at six levels: three cut below level of Mountain View fan in two different channels, one at about fan level, and two at levels higher than that of the Mountain View fan farther up Ship Creek near the Chugach Mountain Front. Thickness is probably several to 10 m.

scl
sclu **Lower-level deposits (Holocene)—**Extend along present course of Ship Creek from Chugach Mountain Front nearly to its mouth, mainly in extensive low terrace that gradually becomes higher to the west. *sclu* are deposits modified by urbanization.

scc
sccu **Chester Creek deposits (early Holocene? and late Pleistocene)—**Occur in channel developed by ancestral Ship Creek when it flowed southwestward from its present northernmost reach and formed channel now occupied by lower course of Chester Creek. *sccu* are deposits modified by urbanization.

sch
schu
schp
schpu **Chester Creek deposits at higher level (late Pleistocene)—**Occur mainly in broad channel cut slightly below level of Mountain View fan when ancestral Ship Creek

first flowed southwestward through valley now occupied by lower course of Chester Creek; there, deposits now found in terrace remnants. *schu* are deposits modified by urbanization. *schp* are deposits overlain by peat about 1 m thick of mainly Holocene age; *schpu* are areas that have been drained and most peat removed during urbanization.

scf scfu **Alluvial-fan deposits (late Pleistocene)—** Thickness may be more than 10 m. Occur in prominent fan that extends along Ship Creek from Chugach Mountain Front to Glenn Highway. Fan appears graded to various levels of Nunaka Valley and Mountain View deposits. *scfu* are deposits excavated in conjunction with regional urbanization.

sct sctu **Terrace deposits (late Pleistocene)—**Occur near head of Ship Creek alluvial fan in remnants of small, higher-level alluvial fan, or of fan-delta graded to level of glacioestuarine water in which Muldoon Road deposits accumulated. *sctu* are deposits excavated in conjunction with regional urbanization.

scth **Highest-level deposits (late Pleistocene)—** Occur near head of Ship Creek alluvial fan in remnants of probable fan-delta graded to level of glacioestuarine water in which Abbott Road deposits accumulated.

*Deposits of North Fork Campbell Creek (late Pleistocene)*. These are subdivided into deposits at three levels. Thickness is probably a few meters, except as noted.

nfl **Lower-level deposits—**Occur in channels on both sides of main alluvial fan of North Fork Campbell Creek that were not necessarily occupied contemporaneously.

nf **Main alluvial-fan deposits—**Thickness probably several to 10 m. Occur in prominent fans along North Fork Campbell and Chester Creeks where they have descended from Hillside area; mapped also in low terrace remnants farther up North Fork Campbell Creek Valley.

nfh nfhf **Higher-level deposits—**Occur mainly in higher part of alluvial fan of Chester Creek; also in single high-terrace remnant along North Fork Campbell Creek. *nfhf* are probably sand and silt with peat at surface; occur in single channel north of Chester Creek.

*Deposits of South Fork Campbell Creek*. These are subdivided into deposits at five levels. Thickness is probably several meters, except as noted.

sfs sfsu **Southern lower-level deposits (Holocene? and late Pleistocene)—**Occur in channel that carried South Fork water at one or more times after deposition of main fan. Channel now contains underfit North Fork Little Campbell Creek, developed from underflow of South Fork Campbell Creek, which currently flows only about 1 m below the level of this channel. There is danger that at times of high water it could reoccupy this channel, perhaps on a long-term basis, and thereby flood at least some part of the channel area. *sfsu* are deposits modified by urbanization.

sfn sfnu **Northern lower-level deposits (late Pleistocene)—**Occupy channel and smaller alluvial fan that could have carried some South Fork and probably all North Fork Campbell Creek waters northward into a combined ancestral Ship Creek and Eagle River. *sfnu* are deposits modified by urbanization.

sf **Deposits of main alluvial fan (late Pleistocene)—**Thickness probably 10 m or more. Occupy prominent alluvial fan lying mainly on south side of South Fork; extend upvalley from apex of fan as low-level terrace deposits.

sft **Terrace deposits (late Pleistocene)—**Occur only in scattered terrace remnants at intermediate levels in upper South Fork Valley.

sfth **Highest-level deposits (late Pleistocene)—** Occur only in scattered terrace remnants at high levels in upper South Fork Valley.

*Alluvial deposits of the lower Hillside area (late Pleistocene)*. These are the deposits of two principal southwest-trending channel and terrace systems that lead to deltas (west of the map area) that formed marginal to ancestral Cook Inlet. Thickness is probably a few to several meters. Contacts are well defined. Topography is smooth, with slopes being gentle to very gentle.

sh shu **Spring Hill deposits—**Occupy channel system that extends from near apex of main alluvial fan of South Fork Campbell Creek and that splits into a more deeply incised channel to the southwest and a shallower

channel to the northwest. Also occur in valley of South Fork Campbell Creek in intermediate-level terrace; remnants higher than deposits of main alluvial fan and lower than deposits of main terrace. *shu* are deposits modified by urbanization.

The **Klatt Road deposits** are subdivided into deposits at the following three levels.

kcl kclu **Lower-level deposits—**Occur mainly in terraces at levels higher than Spring Hill deposits and in channels graded thereto; mapped also in a channel that probably carried water from North Fork Campbell Creek toward the southwest. *kclu* are deposits modified by urbanization.

kc **Main-level deposits—**Occupy major channel system extending southwestward from South Fork Campbell Creek.

kch kchu **Higher-level deposits—**Occur in terrace remnants at levels higher than the main channel and in shallow channels graded to those levels. *kchu* are deposits modified by urbanization.

*Glaciolacustrine, lacustrine, and related deposits*

These deposits are subdivided into five types that accumulated in bodies of water ranging from large lakes to small ponds. Some were closely associated with glaciers, whereas others formed after retreat of the glaciers: 1) Kame-fan deposits are transitional in origin between glacioalluvial and glaciolacustrine deposits. Like kame-terrace deposits, they were deposited along the margin of a glacier, but their (commonly) small source valleys were generally perpendicular to and blocked by the glacier. In part the blockage may have resulted in small ice-dammed lakes, but many deposits seem to have more the character of deltas or alluvial fans. This implies that lakes, if any, were short-lived, and that drainage probably was able to enter the glacier and form the extensive kame fields associated with lateral moraines. 2) Glaciolacustrine deposits accumulated when more permanent lakes did form in commonly large valleys blocked by the glacier. The principal lakes thus formed in this map area, their names derived from the valleys in which they were located, are glacial Lake Eagle (Schmoll et al., in press) and glacial Lake Ship, named here. 3) Deltaic deposits formed locally where streams entered such lakes. 4) Some deposits formed in lakes when glaciers were no longer present in major valleys but where moraines or landslides blocked the valley. 5) Ponds formed in many undrained depressions on the uneven surface of moraines or areas formerly occupied by glacioestuarine water. As the ponds filled, mainly with organic material, they became bogs that no longer contained open water and are now sites of thick peat accumulation.

*Kame-fan deposits.* These are chiefly gravel and sand, well to poorly bedded and sorted, and may include beds of fine sand, silt, clay, and diamicton. Thickness is probably several to a few tens of meters. Contacts are fairly well defined, except where they are commonly gradational with colluvium. Topography is generally smooth, with slopes being moderately gentle to moderate, and locally steep at ice-proximal margins.

ekf **Deposits related to the Elmendorf Moraine (late Pleistocene)—**Occur at a few localities along the Chugach Mountain Front near Carol Creek.

dkf dkfu **Deposits related to Dishno Pond moraines (late Pleistocene)—**Occur commonly at two levels along Chugach Mountain Front near Ship Creek and north of Eagle River Valley, and locally along south side of that valley near mouth of South Fork Valley. *dkfu* are deposits modified by urbanization.

fkf **Deposits related to Fort Richardson moraines (late Pleistocene)—**Occur near mouths of all but the largest mountain valleys along Chugach Mountain Front from Little Peters Creek southwestward to South Fork Campbell Creek, and at a few places along the sides of valleys of Little Peters Creek, Eagle River, and its South Fork.

rkf **Deposits related to Rabbit Creek moraines (late Pleistocene)—**Occur locally in valleys of Eagle River and South Fork Campbell Creek.

lkf **Deposits related to Little Rabbit Creek moraines (Pleistocene)—**May be somewhat more oxidized than younger deposits. Occur prominently in Ship Creek and Snowhawk Valleys, and in the two more northerly Wolverine Valleys where they extend up-valley to include outwash deposits; also found locally in Chester Creek Valley.

skf **Deposits related to Ski Bowl moraines (Pleistocene)—**Probably more oxidized than younger deposits. Occur prominently in Ship Creek and nearby Snowhawk Valleys (the typical area) and locally near

Mount Gordon Lyon and in northernmost Wolverine Valley.

gkf **Deposits related to Glen Alps moraines (Pleistocene)—**More oxidized than younger deposits. Single occurrence in northernmost Wolverine Valley.

*Glacial-lake delta deposits (late Pleistocene).* These are chiefly gravel and sand, generally well bedded and sorted; they may include thin beds of, or be underlain by, finer-grained glaciolacustrine deposits. Thickness is probably 10 m or less. Contacts are generally well defined, but gradational to glacioalluvial deposits up-valley. Topography is generally smooth, with slopes being gentle, except for moderate to steep slopes at small scarps on the down-valley sides.

egd **Deposits related to the Elmendorf moraine**—Occur in Eagle River Valley in prominent landform at mouth of South Fork and farther downstream on both sides of Eagle River.

dgd **Deposits related to Dishno Pond moraines**—Occur in valley of South Fork Eagle River and near mouth of Snowhawk Valley.

fgd **Deposits related to Fort Richardson moraines—**Occur as part of major terrace in Ship Creek Valley and where tributaries entered glacial Lake Ship.

rgd **Deposits related to Rabbit Creek moraines—**Occur along the sides of Ship Creek Valley where tributaries entered glacial Lake Ship**.**

*Glaciolacustrine deposits.* These are interbedded clay, silt, and sand; they may include some gravel and diamicton in varying proportions; they are well to somewhat poorly sorted. Contacts are relatively well defined. Topography is generally smooth, and slopes gentle, except for being very steep at valleyward margins. These deposits are moderately stable except near the contact with valley-wall colluvium, where they are susceptible to stream erosion, earthflowage, or other landslide processes.

egl **Deposits related to the Elmendorf Moraine (late Pleistocene)—**Mainly deposits of glacial Lake Eagle. Thickness 5 to 10 m; may be much thicker beneath alluvial and peat deposits that form the floor of the inner Eagle River Valley, but mapped only marginal thereto.

dgl **Deposits related to Dishno Pond moraines (late Pleistocene)—**Thickness probably about 10 m. Occur 1) in valley of South Fork Eagle River (laid down in an arm of glacial Lake Eagle) and 2) along south side of Ship Creek Valley near Chugach Mountain Front (laid down in a low level of glacial Lake Ship).

fgl **Deposits related to Fort Richardson moraines (late Pleistocene)—**Thickness 10 m or more. Best developed and probably thickest in valley of Ship Creek where laid down in intermediate levels of glacial Lake Ship; distinguished from Rabbit Creek deposits only on altitudinal basis. Occur also in valleys of Meadow and North Fork Campbell Creeks near Chugach Mountain Front.

rgl **Deposits related to Rabbit Creek moraines (late Pleistocene)—**Thickness 10 m or more in Ship Creek Valley where laid down in high levels of glacial Lake Ship; distinguished from Fort Richardson deposits only on altitudinal basis. Probably less than 10 m thick in valley of Meadow Creek.

sgl **Deposits related to Ski Bowl moraines (Pleistocene)—**May be more oxidized than younger deposits. Thickness probably a few to several meters. Occur only in high-level tundra flat north of Ship Creek near area of typical Ski Bowl deposits.

*Lacustrine and related deltaic deposits.* The contacts of these are generally well defined. The surface is smooth to slightly irregular; general slope is less than 1%.

lyd **Young deltaic deposits in Eagle River Valley (Holocene and late Pleistocene)—**Chiefly gravel and sand; may include some beds of silt. Thickness may be as much as 10 m. Occur only in Eagle River Valley near mouth of South Fork.

ly **Young lacustrine deposits in Eagle River Valley (Holocene and late Pleistocene)—**Chiefly interbedded silt and clay, blue-gray; include some beds of fine sand and fine tephra. Thickness probably 10 m or less, base of unit not exposed. Occur only at low levels of inner Eagle River Valley, laid down in a late stage of glacial Lake Eagle or in a subsequent lake blocked by moraine or landslide deposits; may underlie alluvium on valley floor.

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pf **Deposits in Fire Creek Valley (Holocene)—** Deposits not exposed; genesis and character mainly inferential. Probably silt, clay, and fine sand; may include thin tephra beds and peat near surface. Deposits alternatively could be either 1) estuarine, formed in a narrow inlet of Knik Arm, or 2) mainly fine-grained alluvium of Fire Creek. Thickness probably several to a few tens of meters. Contacts gradational to fine-grained alluvium of present Fire Creek. Poorly drained.

p
pu
ppfu **Pond and bog deposits (Holocene and late Pleistocene)—**Chiefly peat (mosses, sedges, and other organic material in various stages of decomposition); include silt, organic-rich silt, minor woody horizons, and a few thin interbeds of mainly ash-sized tephra. At depth also may include clay, marl, or fine to medium sand. Accumulated mainly in former small lakes or in former stream channels that are now bogs. Soft and moist. Thickness commonly as much as 4 m, locally as much as 10 m; adjacent mapped deposits extend beneath these deposits. Contacts well defined, but deposits may grade laterally to the similar but much thinner mantle that overlies adjacent deposits. Surface smooth; slopes less than 1%. Poorly drained. Widespread occurrences within Elmendorf Moraine and on the floor of Eagle River Valley; common locally in areas of lateral moraines and associated channels. Scattered occurrences elsewhere in Anchorage Lowland; most peat there, however, probably did not begin accumulating in ponds, and is mapped with underlying alluvial deposits in map units *schp, evp,* and *wsp. pu* is peat partially or totally removed during urbanization; *ppfu* is an area that probably contained permafrost.

*Glaciolacustrine or glacioestuarine deposits (late Pleistocene)*

These deposits accumulated either 1) in lakes marginal to glacier ice or in narrow valleys marginal to former glaciers when the valleys were blocked by moraine remnants or alluvial fans of mountain-origin streams, 2) in the margins of glacioestuarine waters as they rose, following withdrawal of glacier ice, or 3) in a high-level, basin-wide glacial lake of the type envisioned by Karlstrom (1964).

ev
evpf
evu **Early View deposits—**Dominantly silt and silty clay, locally may include fine sand. Thickness probably a few to several meters. If glacioestuarine, equivalent to part of Bootlegger Cove Formation. Contacts generally well defined. Topography smooth, slopes nearly flat. Occur in broad, channel-like area now occupied by a north-flowing reach of South Fork Chester Creek, commonly downslope from adjacent Muldoon Road deposits. *evpf* is an area containing permafrost; *evu* are deposits modified by urbanization.

evp **Deposits with peat at surface—**Peat about 1 m thick in a few central areas that are apparently less well drained than surrounding areas.

evc
evcu **Coarse-grained deposits—**Probably contain higher proportion of sand (and perhaps some gravel) than remainder of deposits to which they are mainly marginal. Also mapped south of North Fork Little Campbell Creek where finer-grained deposits are lacking and identity is based mainly on geomorphic relationship to adjacent, higher-lying Muldoon Road deposits; here, less likely to be of lacustrine origin. *evcu* are deposits modified by urbanization.

br **Birch Road deposits—**Fine sand and silt, finely bedded and well sorted, especially where typically developed south of map area; here may be coarser-grained or more poorly sorted, or both, and may include sand, gravel, and diamicton, especially near map unit *fk*. Topography fairly smooth to slightly hummocky, slopes gentle. Occur principally in narrow belt that widens southwestward from South Fork Chester Creek and that lies between about 140 and 200 m in altitude. Possibly deposited in a local glacier-dammed lake or in a basin-wide glacial lake.

*Glacioestuarine deposits or moraine and kame deposits modified in a glacioestuarine environment (late Pleistocene)*

These occur in relatively prominent hills in Anchorage Lowland south of Elmendorf Moraine. Formed either as ground moraine and associated kames and subsequently modified by wave and tide action in a glacioestuarine environment, or by redeposition of glacial deposits

that formed near the glacier-glacioestuary boundary and that slumped subaqueously. Most likely some combination of these processes was involved in producing the deposits, but the relative importance of each is uncertain and might have varied both within the same deposit and among the deposits included here.

rj
rju **Russian Jack deposits—**Mainly diamicton; especially at depth may be ground moraine equivalent to Dishno Pond, Fort Richardson, or older lateral moraines; nearer surface includes some interbedded silt, fine sand, and sand and gravel both in well defined beds and as obscurely bedded, discontinuous horizons. Thickness as much as 25 m. Contacts fairly well defined but may be gradational with Muldoon Road deposits in many places. Occur in well-defined hills of smooth topography with gently to moderately gently sloping tops and moderately to steeply sloping sides. Although some hills appear drumlinoid in form, others owe their present configuration to erosion that produced adjacent channels. Widespread between Ship Creek and North Fork Little Campbell Creek. *rju* are deposits modified by urbanization.

*Modified kame deposits.* These are mainly gravel and sand, well to moderately poorly bedded and sorted; they include some interbedded fine sand and silt. Diamicton may be dominant in the cores of hills and also may occur at the surface of the hills. Contacts are well defined. Topography is commonly sharply hilly, with slopes being generally moderate to steep.

dkm **Deposits related to Dishno Pond moraines—**Occur near South Fork Chester Creek at southwestern end of Dishno Pond kame field where it was encroached upon by glacioestuarine water; hills more subdued than those in unmodified part of kame field.

fkm **Deposits related to Fort Richardson moraines—**Extend discontinuously from South Fork Chester Creek to south of South Fork Campbell Creek where lowest-lying hills of Fort Richardson kame field are more subdued than but identifiable separately from hills composed of glacioestuarine deposits.

bp
bpu **Boniface Parkway deposits—**Extend discontinuously from south of Ship Creek to South Fork Campbell Creek. Associated with Russian Jack deposits and may represent more gravelly phase of those deposits or perhaps are remnants of a once continuous esker system originally part of Dishno Pond moraine complex. Occur also near North Fork Campbell Creek in small hills that may be modified kames and thus similar to deposits mapped as *fkm*. *bpu* are deposits modified by urbanization.

or **O'Malley Road deposits—**Mainly in isolated hills that could represent either more gravelly phase of glacioestuarine deposits or partly buried kames that were initially part of Fort Richardson or Rabbit Creek moraine complexes. Occur only near and south of North Fork Little Campbell Creek.

*Estuarine and glacioestuarine deposits*

These are estuarine deposits formed in present-day Cook Inlet and its major arms, Knik Arm and Turnagain Arm, or in similar bodies of water of the recent past with similar configuration and tide characteristics. Glacioestuarine deposits accumulated in an ancestral Cook Inlet that probably differed from the present-day inlet in configuration, in level with respect to the present land surface, and in its association with glacier ice. Over time, however, the ancestral inlet evolved to that of the present day with generally gradual changes in level and configuration.

*Modern estuarine deposits (latest Holocene).* These are deposits that are at least partly still in the transport mode in that they are or have been until very recently reworked by the modern estuary. They have been mapped around the margins of Knik Arm. **Intertidal deposits** are chiefly silt and fine sand; they are somewhat coarser near levees of major tide channels. They are well bedded and sorted, being loose and water saturated. Thickness is less than 1 m to a few meters, probably underlain by several meters of older intertidal deposits. Contacts may vary in location with each tide as well as from season to season and year to year. The surface is generally smooth, but incised 1 m to a few meters by numerous channels that may have steep margins. Slopes are otherwise nearly flat to gentle, commonly less than 1%. These deposits are best developed where adjacent land is not bounded by bluffs.

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il **Deposits of the lower intertidal zone—**In some places include driftwood and gravel in a shoreward-most part of deposit where they form discontinuous storm beach. Reworked twice daily when covered by water at high tides; exposed a low tides. Deposits extend into area mapped as water where they are exposed at low tides. Upper boundary may be a few meters above mean high water.

iu **Deposits of the upper intertidal zone—**Locally more sandy and gravelly than lower-zone deposits, especially in uppermost parts of zone, which are covered by water only at times of exceptionally high tides coupled with major storms. Contain some driftwood and fine gravel as well as finer organic and windblown material. Surface marked by standing water in some areas where drainage is very poor.

ib **Beach deposits—**Chiefly sand with some gravel, well bedded and sorted; locally driftwood laden near base of bluffs. Encompass the lower and upper intertidal zones along base of bluffs in northern part of map area; elsewhere not shown separately from map unit *s* but shown on Figure A3. Near shoreward end of Eagle River Flats, form belt between upper and lower intertidal zones.

*Older estuarine deposits (Holocene).* These are only rarely flooded by present day high tides. They are more firm than modern estuarine deposits. Contacts are well defined, except indefinite in the part adjacent to younger deposits. Topography is smooth, locally incised by channels of small streams; slopes are nearly flat.

io **Intertidal deposits—**Chiefly silt, fine sandy silt, and fine sand, well bedded and sorted; may include some thin beds of peat, driftwood, and other organic material, and windblown material. Thickness commonly several meters to possibly a few tens of meters. Occur extensively in Eagle River Flats and locally near mouth of Fire Creek.

ibo **Beach deposits—**Chiefly sand with some gravel. Thickness probably a few meters. Occur locally marginal to south side of Eagle River Flats.

*Glacioestuarine deposits (late Pleistocene).* These accumulated in a variety of environments in ancestral Cook Inlet. Several different water levels are inferred from deposits at recognizably different, somewhat terrace-like levels; however, no shorelines have been recognized definitively. The land / water interface probably fluctuated repeatedly as glacier fronts withdrew and then readvanced and as world-wide sea level fluctuated, and also as the land surface responded to regional glacioisostatic and tectonic effects. Inlet water was at least partly in contact with glacier ice, as reflected in both the volume and the variety of material types, especially in their relative coarseness and poor sorting. These deposits consist of varying combinations of interbedded diamicton, stony silt, fine sand, silt, clayey silt, and silty clay, with coarser sand and gravel present locally. Contacts are generally well defined; contacts between adjacent glacioestuarine deposits are located only approximately, but deposits are probably not in gradational contact. Topography is commonly smooth but marked locally by small subdued hills or minor surface irregularities; slopes are very gentle to moderate

bc
bcu **Bootlegger Cove Formation—**(Bootlegger Cove Clay of Miller and Dobrovolny [1959]; redesignated as Formation in Updike et al. [1982]). Silty clay and clayey silt with minor interbedded silt, fine sand, fine to medium sand, and thin beds of diamicton, and with scattered pebbles and cobbles in widely varying concentrations. Brackish-marine microfossils are present throughout much of the formation (Schmidt 1963, Smith 1964); mollusk shells in one horizon have an uncalibrated radiocarbon age of about 14,000 years (Schmoll et al. 1972). Thickness as much as 35 m (Updike et al. 1988), quite variable because of irregular lower and upper contacts (Trainer and Waller 1965). Principal deposit of ancestral Cook Inlet during and immediately following withdrawal of glacier ice. Occurs widely in subsurface underlying deposits mapped at the surface from north of the Elmendorf Moraine south to bluffs near Turnagain Arm. Sensitive zones within formation responsible for catastrophic landsliding along bluffs west of map area during large-magnitude earthquakes such as that of 1964 (Hansen 1965). Present knowledge of distribution and age of formation well summarized by Reger et al. (1995). Shown mainly within map unit *s* (Fig. 4). *bcu* is a concealed occurrence at Glenn Highway–Boniface

Parkway interchange that was exposed along Glenn Highway during construction.

ws wsu **Winchester Street deposits—**Chiefly medium to fine sand with some interbedded silt. Thickness probably a few to several meters. May represent marginal facies of estuary that had less contact with glacier ice than older and higher-level estuaries represented by Muldoon Road and Abbott Road deposits. Occur mainly between Chester Creek and North Fork Little Campbell Creek near west edge of map area. *wsu* are deposits modified by urbanization.

wsc wscu **Coarse-grained deposits—**Dominantly sand and gravel. A few terrace-like occurrences mainly adjacent to hills of Muldoon Road and Russian Jack deposits. *wscu* are deposits modified by urbanization.

wsp wspu **Deposits with peat at surface—**May include finer-grained material than elsewhere within these deposits. Peat commonly more than 1 m thick. Bootlegger Cove Formation may be present at shallow depth. *wspu* is peat removed during urbanization; permafrost subsequently reported.

mr mru **Muldoon Road deposits—**Chiefly fine sand and silt; locally include interbedded diamicton or may consist mainly of crudely bedded fine-sandy diamicton. Thickness probably several meters. Interpreted as reworking of ground moraine as inlet water encroached upon areas abandoned by glacier ice. Widespread between Ship Creek and South Fork Little Campbell Creek, commonly lower than about 110 m in altitude in lower terrain surrounding hills of Russian Jack deposits into which they may grade or onto which they may lap. *mru* are deposits modified by urbanization.

ar aru **Abbott Road deposits—**Chiefly diamicton, crudely bedded to massive, with some interbedded silt and fine sand; coarser sand and gravel may be present locally. In belt about 1 to 2 km wide along Abbott Road, contain high proportion of rubble in near-surface exposures, possibly the result of a landslide emplaced either on glacier ice or directly in estuarine water shortly after ice withdrew. Thickness several to about 10 m. Alternately may represent ground moraine only somewhat modified by encroaching estuarine water as ice melted and ice front receded. Extend in a relatively narrow belt from North Fork Campbell Creek to south edge of map area at an altitude between about 110 and 140 m, just downslope from Birch Road deposits. *aru* are deposits modified by urbanization.

*Alluvial deposits*

These are subdivided into deposits formed by streams 1) along their normal courses and found at or near stream level, as well as in terraces well above stream level, and 2) in alluvial fans at one or more levels.

*Alluvium along streams.* These deposits are chiefly gravel and sand formed in present-day streams, ancestral streams, and some older streams no longer present that lack any direct association with glaciers; they include some fine-grained deposits. Generally, they are well bedded and sorted, with clasts commonly rounded to well rounded. Thickness is variable, probably a few to several meters; it may be 10 m or more in large valleys and in large alluvial fans. Contacts are well defined. Topography is smooth, with slopes being nearly flat to very gentle, and steeper on alluvial-fan deposits. Steep scarps 1 m to several meters high separate deposits at different levels between adjacent map units and locally within map units.

aa **Alluvium in active floodplains (latest Holocene)—**Gravel and sand transported intermittently and deposited temporarily in bars that commonly change their position along braided and single channels. Vegetation cover generally absent or just beginning to develop in areas that have not been affected directly by the stream for a few years. Area subject to continuing erosion and flooding; in places stream may encroach upon areas adjacent to area of map unit. Mapped mainly along Eagle River and locally along Ship Creek.

al alu **Alluvial deposits along modern streams and in lowest terraces (Holocene)—**Chiefly gravel and sand except in the Eagle River Valley up-valley from South Fork confluence where sand is more common and overlies lacustrine silt and clay at depths of about 7 m. Generally less than a few meters above stream level. Include some material of active floodplains still partly in transport mode in areas too small to map

separately. Mapped mainly along major streams; occur also along small streams in areas too narrow to map separately. *alu* are deposits modified by urbanization.

alf alfu **Fine-grained deposits along some minor streams—**Chiefly silt and fine sand; may include some peat deposits near surface. Occur mainly along parts of Mink and Fire Creeks and the Otter-Sixmile channel, and locally where small low-gradient streams cross low-lying areas. *alfu* are deposits modified by urbanization.

at **Older alluvial deposits in terraces (Holocene)—**Chiefly gravel and sand, commonly several meters above stream level. Occur locally along Clunie Creek and Eagle River.

ath **Deposits in higher terraces (Holocene and late Pleistocene)—**Still older alluvium occurring in local remnants about 10 m above Meadow Creek and at least 5 m above the lower reaches of Eagle River.

alo **Older alluvial deposits in channels (Holocene and late Pleistocene)—**Chiefly gravel and sand in channels abandoned by stream that formed them and that are now occupied, if at all, by underfit streams. Thickness probably only 1 m to a few meters. Mapped only in a few places along tributaries to Ship Creek and in the Hillside area between North and South Forks of Campbell Creek.

*Alluvial-fan deposits*. These formed near the mouths of large streams and where small tributary streams enter larger streams that have lower gradients. They are graded to or just above modern stream levels. Slopes are moderately gentle to moderate, steeper near the heads of fans.

af afu **Coarse-grained deposits (Holocene)—**Chiefly gravel and sand; dominantly gravel in large fan near mouth of Peters Creek and possibly in large fan near mouth of Clunie Creek and where Eagle River enters Eagle River Flats; in moderate to small fans common in many valleys may be somewhat less well sorted than other alluvium, and locally include silt and diamicton beds resulting from minor mudflows. *afu* are deposits modified by urbanization.

aff **Fine-grained deposits (Holocene)—**Chiefly fine sand and silt; locally may include coarser sand and some gravel. Occur marginal to intertidal deposits, in and adjacent to low-lying, nearly flat channels, and in a few other localities where minor streams cross areas of substantially lower slope than areas just upstream.

afo afou **Older alluvial-fan deposits, undivided (Holocene and late Pleistocene)—**Gravel and sand, possibly admixed with some finer-grained material and thin diamicton beds. Deposits typically less well sorted and more steeply sloping than those in other alluvial units. Occur commonly as remnants associated with younger alluvial fans, but graded to levels well above modern streams. Near mouth of Clunie Creek represent slightly older part of main fan. Common on lower parts of mountain-valley walls and present at a few places along Chugach Mountain Front. *afou* are deposits modified by urbanization.

afp afpu **Deposits along Peters Creek—**Chiefly gravel with some sand. May be fan delta graded to a level above present sea level, and possibly latest Pleistocene in age; alternatively, might have extended substantially farther northwest into Knik Arm, and be graded to near present sea level but eroded to present distribution. Slopes very to moderately gentle, gradually increasing to steep near head of fan. Much material removed as major source of gravel and sand, especially near toe of fan. *afpu* are deposits modified by urbanization.

*Colluvial deposits*

The term colluvial deposits (colluvium), as used here, includes those deposits that occur on slopes and that have accumulated primarily through the action of gravity and, secondarily, through the action of running water. Colluvium is broadly subdivided into 1) deposits that have accumulated particle by particle over a long period of time, and 2) those deposits that have moved en masse. Among those in category 1 are deposits on mountain slopes, deposits derived mainly from moraines, and deposits on bluffs along streams and along Knik Arm. Those in category 2 include both slow-moving solifluction deposits as well as a variety of landslide deposits, most of which have been emplaced rapidly. Most colluvial deposits are relatively poorly sorted and many are not well compacted; because of their location on slopes, they are subject to instability especially when excavated.

c **Colluvial deposits on mountain slopes (Holocene and Pleistocene)—**Mainly apronlike deposits of loose, sandy to rubbly diamicton derived directly from weathering of bedrock upslope; include some sheetwash deposits. Thickness probably less than 1 m to several meters, thicker on lower parts of slopes. Contacts gradational. Topography smooth, surface gently concave, slopes generally steep to very steep, but usually not in excess of 70%. Commonly veneered by thin, low vegetation. Some instability likely. Occur on mountain slopes in a belt downslope from mapped bedrock.

ct **Talus deposits (Holocene)—**Cone-shaped to apronlike deposits on valley walls within rugged mountains. Mainly loose, coarse rubble, and rubbly diamicton derived directly from weathering of bedrock upslope. Thickness variable, generally thickest in middle to lower parts of cones and aprons, probably several to a few tens of meters, thinning gradually upward towards apexes and more abruptly downward near toes. Contacts generally gradational, to bedrock at apex and to other mapped units at toe; individual cones commonly have well-defined boundaries, however. Talus deposits too small to map separately are included in bedrock map unit. Topography smooth, slopes steep to very steep, as much as 100% near apex, rarely less than 35% near toe. Commonly free of even low vegetation and subject to continuing deposition from upslope, including rockfalls and debris-laden snow avalanches; slopes generally unstable. Occur locally on highest and in association with steepest mountain slopes.

ca **Colluvial and alluvial deposits (Holocene)—**Areas of colluvium and alluvium too small to map separately. Chiefly moderately loose, sandy to rubbly diamicton, poorly sorted sand and gravel, and some organic debris. Thickness probably a few meters. Contacts generally gradational. Topography irregularly gullied, slopes steep to very steep, generally ranging between 35 and 70%. Commonly covered by at least low vegetation, but vegetation may be lacking in some gullies where active deposition is occurring. Some instability of slopes likely. Occur in small valleys and gullies in mountains, especially near heads of small valleys.

cg **Mixed colluvial and glacial deposits (Holocene and Pleistocene)—**Diamicton; may include chiefly gravelly to rubbly sand, with some silt and clay; locally bouldery. Derived from both bedrock and glacial deposits, either of which may be present in areas too small to map separately. Poorly bedded and sorted. Loosely to moderately compacted in most places. Thickness a few to several meters. Contacts gradational. Slopes smooth to slightly irregular, steep to very steep. Common along middle slopes of most major mountain valleys and along Chugach Mountain Front where glaciers formerly abutted the slope but few identifiable glacial deposits are present at the surface.

cm **Colluvial deposits derived mainly from moraines (Holocene and Pleistocene)—**Diamicton similar to that of adjacent upslope moraines, but less compact. Include minor amounts of better-sorted sand, silt, and gravel that occur in irregular beds and that may have been derived from better-sorted glacial deposits and moved partly with the aid of running water. Commonly a few meters thick. Contacts generally gradational, especially upslope. Slopes generally moderate and moderately stable. Commonly associated with lateral moraines along the Chugach Mountain Front and in a few places in mountain valleys.

cw **Colluvial deposits on walls of inlet and**
cwu **stream bluffs (Holocene and late Pleistocene)—**Loose accumulations that are derived from adjacent, upslope surficial deposits and that form a veneer on bluffs after active erosion has ceased. Chiefly diamicton, consisting of pebbly silt and sand with some clay, cobbles, and boulders, and a variable amount of organic material. Massive to poorly bedded; poorly sorted. Generally a few meters thick, thinner at the upslope part; usually thicker downslope. Contacts generally well defined. Slopes steep to precipitous. Although stabilized locally by vegetation, subject to instability because of renewed erosion and accompanying mass-wasting processes. Occur commonly along bluffs developed in surficial deposits along Knik Arm and along valley walls of major streams where they cross the Anchorage Lowland. Locally present on scarps bor-

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dering deeper and wider channels within the lowland and within lateral moraines along the Chugach Mountain Front, along inner valleys cut lower than the floors of major mountain valleys, and in some narrow gullies cut into mountain-valley walls, notably along the south side of North Fork Campbell Creek. *cwu* are deposits modified or completely removed during urbanization.

cwb cwbu **Deposits that conceal Bootlegger Cove Formation (Holocene)—**That formation itself likely to be present behind lower part of bluff. Possibly subject to development of large landslides especially during great earthquakes such as the 1964 Alaska earthquake. Occur only along Ship Creek near west edge of map area. *cwbu* are deposits mainly removed in conjunction with urbanization.

cwf **Fine-grained deposits—**Chiefly silt, clay, and fine sand; massive to poorly bedded, poorly sorted. Thickness probably a few meters. Slopes irregularly moderate to steep and particularly subject to instability. Occur along walls of inner valleys within mountains adjacent to lacustrine deposits, and locally along Knik Arm northeast of Eagle Bay where fine-grained materials, possibly the Bootlegger Cove Formation, are present in bluffs behind this colluvial veneer.

cs **Solifluction deposits (Holocene and Pleistocene)—**Chiefly loose, organic-rich, sandy to rubbly diamicton, commonly lacking clasts larger than pebble size. Derived mostly from weathering of frost-shattered bedrock directly upslope, seasonally moving very slowly down broad mountain slopes either with the aid of interstitial or underlying ice (solifluction in a strict sense) or of water derived largely from snowmelt. Thickness probably 1 m to a few meters. Contacts gradational to 1) very thinly concealed bedrock, 2) other colluvium, and 3) thicker accumulations of material that has moved downslope by landsliding; include some landslide deposits too small to map separately. Topography generally fairly smooth, but with many minor irregularities, especially in the form of small lobes with flatter upper surfaces and steeper fronts. Slopes steep to moderately steep. Generally unstable. Occur at scattered localities on mountain slopes, especially on middle and lower slopes.

cl **Landslide deposits, undivided (Holocene and late Pleistocene)—**Include a wide variety of materials, chiefly diamicton, with lesser gravelly silt and sand, and relatively minor amounts of clay and organic material; locally include rubble and some large masses of bedrock. Earthflow deposits too small to map separately present locally. Massive; nonsorted to poorly sorted. Relatively loose. Thickness probably several meters to possibly several tens of meters locally in large landslides. Contacts moderately well to poorly defined. Topography irregular to hummocky, slopes moderate to steep. Queried deposits alternately may be rock-glacier, moraine, or other colluvial deposits, or even in-place bedrock. Occur in many places on mountain slopes, and locally in mountain valleys associated with glaciolacustrine and lacustrine deposits, on inlet and stream bluffs associated with wall colluvium, and on a few hills within the Elmendorf Moraine.

clb **Older landslide deposits involving Bootlegger Cove Formation (Holocene)—**Probably gravel, sand, silt, and clay partly mixed to form poorly compacted diamicton. Occur locally along south side of lower Ship Creek Valley near west edge of map area.

cld **Landslide deposits related to Dishno Pond moraines (late Pleistocene)—**Identity postulated largely on basis of landforms similar to but more subdued than adjacent lateral moraines and kames, the lateral continuity of which is lacking in area of these deposits. Mainly diamicton, gravel, and sand. Occur downslope from Chugach Mountain Front south of Ship Creek.

clm **Deposits possibly modified in a glacioestuarine environment—**Landforms even more subdued in this lower-lying area may have been reworked subaqueously shortly following deposition.

clg **Landslide deposits involving glacioestuarine deposits (Holocene and late Pleistocene)—**Identity postulated largely on basis of irregularly lumpy, crudely lobate topography in areas of channels adjacent to higher-lying glacioestuarine deposits. Occur south of South Fork Chester Creek and northeast of alluvial fan of South Fork

Campbell Creek.

cle **Landslide deposits resulting from earthflows (Holocene and late Pleistocene)—** Similar to other landslide deposits within the mountains, but interpreted on the basis of landform to have been emplaced in a probably more fluid state and therefore may include a higher proportion of finer-grained material. Contacts generally well defined. Mainly in long, narrow occurrences in gullies and small valleys within Chugach Mountains.

*Rock glaciers and rock-glacier deposits*

Rock glaciers may be regarded as transitional between true glaciers and a kind of active, slow-moving landslide, and their deposits are likewise transitional between ground-moraine and colluvial deposits.

rg **Active rock glaciers (latest Holocene)—** Accumulations of mainly angular to some subrounded rock fragments still actively being transported, derived from upslope talus deposits or directly from bedrock. Contain ice-rich matrix and move very slowly downslope. Surface generally lacks vegetation, dominated by cobble- and boulder-size fragments. At depth, substantially more fine-grained material may be present to form coarse, rubbly, massive, and poorly sorted diamicton; at greater depth, dominantly clear glacier ice may be present, as reported in some rock glaciers (Moore and Friedman 1991). Thickness several to a few tens of meters. Contacts generally well defined except gradational to talus at upslope margin. Surface moderately hummocky and rough; slopes generally moderate but steep to very steep along Front and some side margins. Unstable because of continuing very slow movement and potential for melting of ice-rich matrix. Occur mainly at heads of valleys near Tikishla and Temptation Peaks in southeastern part of map area.

rd **Rock-glacier deposits (late Holocene)—** Similar to material of active rock glaciers, but may contain less interstitial ice or less (perhaps no) clear ice at depth. Movement probably has ceased and these deposits are sometimes termed inactive rock glaciers; however, distinction between the two forms may be difficult to make, or a rock glacier may be alternately active and inactive over a period of years. Some vegetation covers surface. Generally more stable than active rock glaciers, but some instability likely, especially if excavated, because of loose nature of material and likelihood that some interstitial ice may be present and that some massive clear ice may be present at depth. Occur in southeastern part of map area down-valley from rock glaciers, and in some nearby valleys that no longer contain active rock glaciers at their heads.

rds **Deposits of valley-side source (Holocene)—**Similar to other rock-glacier deposits but appear to have headed in and derived from colluvial deposits along the side of long, narrow valleys. Probably do not have, and may never have had, clear-ice cores of any significant thickness. Appear to have originated as coalesced lobate rock glaciers. Occur prominently as major valley fills in Snowhawk and North Fork Campbell Creek Valleys.

rdo **Older rock-glacier deposits (Holocene and late Pleistocene)—**Similar to younger rock-glacier deposits but with somewhat more subdued surface that is more completely covered by low vegetation. Surface somewhat resembles that of ground moraine, but is more finely hummocky rather than smooth, reflecting presence of angular to subangular cobble- and boulder-size fragments just beneath vegetation cover. Not moving as an active rock glacier and unlikely to contain glacier ice, although permafrost likely to be present locally. Occur in several small valleys in southeastern part of map area, commonly in valleys at altitudes lower than the valleys containing younger rock-glacier deposits or active rock glaciers.

*Anthropogenic deposits (latest Holocene)*

f **Engineered fill—**Chiefly compacted pebble gravel, in many places underlain by more poorly sorted sandy to silty gravel, both emplaced to engineering specifications. Includes some areas where a more heterogeneous assemblage of material may have been emplaced without utilizing engineering specifications; in a few places includes land areas extensively modified by earth-moving or rock-quarrying equip-

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ment. Thickness as much as several meters. Contacts well defined, but width shown on map may be exaggerated to accommodate linear base-map symbols provided for roads and railroads. Mapped mainly along Glenn Highway and the Alaska Railroad, at some airfield runways, and along some streets within the urbanized area, especially where they cross low-lying places. Minor fill for roads not shown.

**Bedrock**

Bedrock is not shown in detail here. It is subdivided into two units, younger bedrock and older bedrock. Younger bedrock comprises sedimentary rocks of Tertiary age and is confined to a few outcrops in the margins of the Anchorage Lowland. Older bedrock includes rocks of both Chugach and Peninsula tectonostratigraphic terranes (Coney and Jones 1985, Jones et al. 1987, Silberling et al. 1994) and consists of variably metamorphosed sedimentary and igneous rocks. It is exposed only in the Chugach Mountains and in narrow canyons where major streams are incised in the Hillside area and just northwest of the mountain Front. Where mapped on mountain slopes, bedrock may be concealed by thin colluvium.

by **Younger bedrock (Tertiary)—**Continental rocks, mainly sandstone, siltstone, claystone, and minor coal of the Kenai Group (Calderwood and Fackler 1972). Tyonek Formation (Wolfe and Tanai 1980) is exposed locally along lower course of the Eagle River where two fossil-plant localities have been examined by Schaff (1964) and by Wolfe et al. (1966). It is likely that this is the formation present at scattered roadcut localities within about 2 km of the Chugach Mountain Front in the vicinity of the community of Eagle River, and northward along the Glenn Highway (Dobrovolny and Miller 1950, Schmoll et al. 1971, Zenone et al. 1974). Similar rocks may occur in poor exposures along the Glenn Highway about 3 km south of the Eagle River. Several meters exposed at a few places along the Eagle River, but only 1 m or a few meters in roadcuts. Kenai Group present at depth beneath surficial deposits throughout most of the Anchorage Lowland, where thickness of surficial deposits may be as much as 100 m. About 15 km southwest of the Eagle River, however, Sterling Formation (overlying the Tyonek) has been tentatively identified (Stricker et al. 1988) in a drill hole (Yehle et al. 1986), and this formation probably constitutes part of the total thickness of Kenai Group rocks southwest of the Eagle River.

bo **Older bedrock (Tertiary to Permian)—** Predominantly rocks of the Chugach terrane: McHugh Complex occupies most of the mountainous area; Valdez Group occurs near South Fork Eagle River and on part of the ridge between it and Ship Creek Valley. Rocks of the Peninsula terrane crop out in the margins of the Anchorage Lowland and may occur on ridges near Parks and Little Peters Creeks as well. The two terranes are separated by the Border Ranges fault (MacKevett and Plafker 1974) which, however, is mainly or perhaps entirely concealed beneath surficial deposits within the map area. McHugh Complex (Clark 1973) consists principally of a metaclastic sequence including variably metamorphosed graywacke, argillite, phyllite, and conglomeratic graywacke; locally consists of a metavolcanic sequence including greenstone, metachert, cherty argillite, and argillite. Valdez Group includes principally metagraywacke, metasiltstone, and argillite; felsic to intermediate hypabyssal intrusive rocks are present in and west of the canyon near the mouth of the South Fork Eagle River. Peninsula terrane rocks consist mainly of metasedimentary and metavolcanic rocks including metasandstone, metachert, siliceous argillite, marble, and greenstone (descriptions and distribution from Clark 1972 and Winkler 1992).

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**14. ABSTRACT**

The surficial geology and glacial stratigraphy of Fort Richardson are extremely complex. Recent mapping by the USGS shows the general distribution of surficial deposits, but details on the underlying stratigraphy remain poorly known, leaving a critical gap in the understanding of ground water conditions below Fort Richardson. A conceptual model of the subsurface stratigraphy was developed on the basis of results of recent surficial mapping, current knowledge of the glacial history, studies of modern glaciers, and limited subsurface data. A confining layer below the southern half of the cantonment is likely the northern extension of an "older" ground moraine that crops out further to the south. Below the cantonment, this moraine is buried below about 15 m of outwash and fan deposits, but it appears to be absent to the north, where the confined and unconfined aquifers are hydraulically connected. The northern limit of the "continuous" ground moraine is roughly below the cantonment and parts of Operable Unit D. Buried silt horizons in the fan probably create the locally perched aquifers; however, erosional remnants of the ground moraine and interfingering of debris flow deposits along the Elmendorf Moraine are plausible alternatives. These deposits are composed of finer-grained materials that slow ground water infiltration and cause water to accumulate.

**15. SUBJECT TERMS**

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**Plate 1. Surficial Geology Map of Fort Richardson and Vicinity, Alaska.**
(separate pdf file)

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